UNIVERSITY OF STRATHCLYDE
DEPARTMENT OF ELECTRONIC AND ELECTRICAL ENGINEERING

ADDRESSING SUSTAINABILITY OF OFF GRID POWER IN DEVELOPING COUNTRIES: A CASE STUDY OF MALAWI

By

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This thesis is submitted in partial fulfilment for the degree of Master of Philosophy in Electronic and Electrical Engineering under the auspices of the University of Strathclyde

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DECLARATION

I declare that, except where due acknowledgment has been made; this dissertation is my own work and has not been previously submitted for any other degree or diploma in any institution.

Kelvin Mbizi Tembo

ABSTRACT

The research literature on rural electrification in developing countries shows that sustainability still remains a major challenge. Interest in the developing countries of sub-Saharan Africa is often focused on solar photovoltaic (PV) systems in line with the abundant solar resource. Furthermore, because of the lack of access to electricity grids to the majority of the population in many of these countries off-grid power systems for rural communities are acknowledged as an important aspect of rural electrification strategies. Many planners and decision makers agree that the off-grid PV system has become a valued and straightforward source of electricity for these communities.

However, there are several challenges that need to be addressed to realize the potential of PV as a sustainable solution. These challenges include many reported cases of poor sustainability/longevity, low rates of electrification for the poor/rural communities and a lack of local community participation in the ownership and management of the solar PV systems. The research reported in this dissertation includes a substantial literature review of PV systems in off-grid applications in Africa and this shows that there is inadequate information and data (technical, economic and social) on how these sustainability issues for solar PV systems can be addressed.

This research is supported by real case studies of off-grid PV installations in Malawi which are part of the Community Rural Electrification and Development (CRED) project supported by the Scottish Government with academic and government partners in Malawi. As well as the results of the literature review, this thesis also presents results from a case study of five PV installations in rural communities in Malawi and links this to the Government of Malawi growth strategy and the ongoing efforts to bring electricity to the rural areas of the country. Analysis of social, economic and technical data from the five communities is provided and conclusions are drawn on key sustainability metrics for rural electrification. These are discussed with reference to emerging sustainable development frameworks so that the merits (and limitations) of the approach in this project are clear. Added interest in this dissertation lies in addressing sustainable development issues for energy in a broader sense than simply renewable technologies and also in viewing sustainable energy from a global perspective rather than taking a narrower view of developed countries only.

Key words: Rural Electrification, Sustainability, Renewable Energy, Developing countries

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Although I see this thesis as a milestone for myself, I realize that I still have a lot to learn and I feel excited as my research work continues.

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LIST OF ABBREVIATIONS AND ACRONYMS

AM	Air Mass
AFREPREN	African Energy Policy Research Network
ADF	African Development Fund
ADB	African Development Bank
APINA	Air Pollution Information Network Africa
AC	Alternating Current
BARREM	Barrier Removal to Renewable Energy in Malawi
BSPVS	Battery Based Standalone Photovoltaic System
CRED	Community Rural Electrification and Development
CZ	Czochralski
CO_2	Carbon Monoxide
DWASCO	Dwangwa Sugar Corporation
DC	Direct Current
DoE	Department of Energy
ESCOM	Electricity Supply Commission of Malawi
ESCO	Energy Service Company
ESMAP	Energy Sector Management Assistance Program
EVA	Ethylene Vinyl Acetate
EWEA	European Wind Energy Association
E.COMM	Energy Committee
FSP	Financial Standard Foundation
G8 AIIC	G8 Africa Infrastructure Investment Conference
GoM	Government of Malawi
GEF	Global Environmental Facility
GTZ	Germany Technical Cooperation
GW	Giga Watt
HSA	Health Service Advisor
IMF	International Monetary Fund
IPCC	Intergovernmental Panel on Climate Change

IEC	International Electrotechnical Commission
ISP	Infrastructure Support Project
IEA	International Energy Agency
ITG	Intermediate Technology Development Group
IGBT	Insulated Gate Bipolar Transistor
kW	Kilo Watt
kWh	Kilo Watt-hour
kV	Kilo Volt
kAh	Kilo Amp hour
LED	Light Emitting Diode
MGDS	Malawi Growth Development Strategy
MDG	Millennium Development Goals
MW	Mega Watt
MPPT	Maximum Power Point Tracker
MJ	Mega Joule
MOS	Metal Oxide Semiconductor
MBS	Malawi Bureau of Standards
MCC	Millennium Challenge Corporation
MERA	Malawi Energy Regulatory Authority
MAREP	Malawi Rural Electrification Programme
MEJN	Malawi Economic Justice Network
NEPAD	New Partnership for Africa's Development
MVP	Millennium Village Project
MK	Malawi Kwacha
NRS	National Rationalized Specification
NEP	National Energy Policy
NSREP	National Sustainable Renewable Energy Programme
OECD	Organization for Economic Co-operation and Development
OPEC	Organization of the Petroleum Exporting Countries
PRD	Program Reference Document
PV	Photovoltaic

PWM	Pulse Width Modulation
PPIAF	Public Private Infrastructure Advisory Facility
PROBEC	Programme for Basic Energy and Conservation
REEEP	Renewable Energy and Energy Efficiency Partnership
RET	Renewable Energy Technology
SADC	Southern African Development Community
SAPP	Southern Africa Power Pool
SHS	Solar Home System
STC	Standard Test Condition
SSA	Sub Saharan Africa
SUCOMA	Sugar Corporation of Malawi
SOBO	Southern Bottlers
SEI	Solar Energy International
SCI	Solar Cooker International
SWAP	Sector Wide Approach
SURE	Renewable Energy for Sustainable Livelihood
TW	Tetra Watt
TBA	Traditional Birthing Assistant
USA	United States of Malawi
USD	United States Dollar
UNDP	United Nations Development Programme
UNESCO	United Nations Education and Scientific Commission
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
UN	United Nations
USD	United States Dollar
WHO	World Health Organization
Wp	Watt Peak

1 Chapter 1: Introduction

1.1 Introduction

This chapter discusses the energy sources and key energy problems prevalent in Sub Saharan Africa and provides a summary of the status of the energy sector based on best available information. The energy situation in Malawi that is similar to that in other Sub Saharan region is discussed. The discussion has been kept limited because this research study concentrates on exposing the chronic energy shortage in Sub Saharan region and then highlights that renewable energy such as solar PV can be a solution to energy challenges and can assist to narrow the widening rural and urban electrification levels.

1.2 Background and Justification

Substantial evidence has shown Som (1979) that Malawi is endowed with abundant solar energy that can be converted to electrical energy by means of solar PV systems. In spite of this a majority of Malawians are without electricity in their homes and most affected are those living in the rural areas. Indeed, Government of Malawi (2002) reports that only about 7% of the population has access to electricity out of which less than 1% that lives in the rural areas has access to electricity. Similarly, available evidence shows Estachea et al (2008) that Africa enjoys the most abundant energy reserves in the world and yet its population suffers from one of the lowest electricity access rates. Additionally, access rates of electricity mostly favour urban areas. In Malawi the low electrification levels are further escalated by the fact that the bulk of Malawi's electricity is generated by ESCOM mainly through hydropower. However, generation of electricity by the sole utility company has been significantly hampered by environmental problems. Particularly, siltation of the Shire River has grossly affected the generation capacity and consequently the supply of power to the industrial and domestic sectors has become unreliable. Moreover, there is growing evidence Mnella (2007) that the rate of expansion of ESCOM's system is declining instead of growing. At same time Mnella (2007 & Openshaw (2009) have confirmed that the demand for energy for domestic and industrial purposes continues to expand despite the decline in ESCOM's performance. Correspondingly, Barry (2008) has indicated that energy demand in Southern Africa has gradually increased with consequential need for short, medium and long term interventions to ensure sustainability of energy. On one hand MGDS (2006-2011) has noted that one of the key energy-related issues in

Malawi is to increase the penetration of electricity into rural areas that are not currently served by the national grid. Many recent studies have focused on renewable energy technologies to provide a feasible alternative energy source for rural electrification. Although solar PV systems have been linked to rural electrification, there is little evidence of progress in Malawi. So far, MGDS (2006-2011) has highlighted the fact that implementation has been limited to technology development, demonstrations, and commercialisation by installers and suppliers to establish market for their products and services. Similarly, substantial evidence has shown White (2004) that very few studies have been done on solar PV system sustainability which is one of the crucial factors in socio-economic development. By the same token, UNDP (2010) argue that solar PV systems sustainability poses a major challenge in Malawi and the solar PV technology is at risk of collapsing if proper measures are not taken into account. For example, UNDP (2010) cite that the government of Malawi rural electrification policies and planning, which have a major influence on project outcome, do not explicitly express solar PV system sustainability issues at project design and implementation. Currently, the government of Malawi is promoting the use of solar PV systems for rural electrification however the efforts of increasing rural electrification will yield nothing if issues of solar PV systems sustainability are not taken into account. It is against this background that the research study is designed to highlight and demonstrate possible solutions to the challenges facing solar PV technology in Malawi. In this case, the research work presents a case study of the contribution of solar PV systems as an energy supply and the importance of monitoring the performance of solar PV systems in their normal working environment which can contribute significantly towards sustainability of the technology.

Undoubtedly, one of the major factors to solar PV sustainability is the monitoring of performance. Several writers Dyk et al (2000); Tang et al (2006); So et al (2008); Nkhonjera (2009) & Sample et al (2009) have shown that performance and degradation of solar PV modules are strongly dependent on meteorological conditions such as shading, irradiance, PV array surface temperature, wind speed, humidity etc. These loss factors must be evaluated and analyzed accurately to determine solar PV system performance characteristics. Furthermore, Carr (2005) has provided evidence that solar PV module technologies have different seasonal patterns that are linked to variation of voltage and current temperature coefficients, photo degradation and thermal annealing. It is also argued that solar PV module technologies are rated at Standard Test

Conditions (STC) of 1,000 W/m^2, Air Mass 1.5 and module temperature of 25^{0}C and these do not reflect typical working experience of the solar PV module technologies under normal operating outdoor conditions. It is for this reason that outdoor performance should be monitored to ensure system sustainability. However, Nkhonjera (2009) echoes that although considerable research has been devoted to solar PV systems as an alternative source of energy in Malawi, rather less attention has been paid to solar PV system sustainability in terms of assessing performance in their normal outdoor working conditions.

Therefore, the objective of this research study is twofold: firstly, to assess the outdoor performance of the panel technology used in the Community Rural Electrification project (i.e. Mono-Crystalline Silicon module). Thereafter, the performance data will be evaluated to demonstrate technical sustainability. It is envisaged that the research study will assist in enrichment of knowledge on technical sustainability of solar PV systems in Malawi. Furthermore, the research study will assist planners to get more accurate information on selection of solar PV modules for a particular area and estimate the potential performance of solar PV installations in Malawi. Secondly, this research study will review recent studies on energy sustainability in Sub Saharan Africa. The literature review will cover studies that have analyzed past failures, identified the root causes of poor sustainability and recommended sustainability frameworks that include social, economic, political and other key factors. Recent energy projects (particularly PV) in Malawi will be reviewed in light of the above studies with conclusions drawn on possible approaches that would improve the sustainability of PV systems in Malawi by considering not just the technical considerations but the overall sustainability picture. Results from a small pilot project will be presented and assessed to quantify the potential impact of a sustainable approach to PV systems in Malawi.

1.3 Research Objectives

1.3.1 General Objective

The objective of the research study is to develop a primary source of quantitative technical and socio-economic solar PV systems data from installations in rural areas, establish current challenges to low sustainability and identify and evaluate potential solutions.

1.3.2 Specific Objectives

- Study the present solar PV systems in rural areas of Malawi (CRED Centres). Despite the positive impact, most solar PV electrification programmes are faced with the challenge of being sustainable. Systems work effectively within the first three years. However, a common pattern is for development partners to pull out and handover the project to the local people and three years later the systems are simply abandoned. In order to argue for the need for improved sustainability of solar PV systems, it is important to demonstrate the operational problems with the existing solar PV systems in Malawi as well as Sub Saharan Africa and compare with CRED Community Based operational model.

- Assess the outdoor operational performance of Mono Crystalline Silicone PV Modules in-situ in Chikwawa and Chiradzulu District. In many situations in Malawi where solar PV systems are implemented, these systems quickly fail as a result of lack of monitoring the performance of the solar PV systems. Solar PV monitoring is an important component that provides necessary systems' information to qualified technician so that planned maintenance can be carried out to prevent further deterioration of the system.

- Analyze technical, economic and social data to demonstrate sustainability. Here the socio-economic data will assist to assess to what extent the CRED project has stimulated the living standards of the local community and the technical data will aid in appraisal of the system operation and consequently improve the system sustainability through improved maintenance.

1.4 Research Contributions

1.4.1 Scientific Relevance

Most of the research has addressed issues such as dissemination, financial mechanism, institutional arrangements and socio-economic impact of solar PV systems as a means of rural electrification. However, the technical and social- economic sustainability of solar PV systems have received less attention. No research is known to have tackled the deployment of solar PV in rural areas and at the same time looking at the systematic integration of technical and socio-economic sustainability issues at the inception of the projects in Malawi. The present research study undertakes such a task. The research study links theoretical knowledge, practical experience and the project findings with the aim of increasing the specific expertise needed for technical and social-economic solar PV sustainability issues. In this respect the study also aims to bridge the gap between theoretically based researchers and a more practical approach. The research study is also aligned with the government of Malawi rural electrification strategy and the CRED projects targets of improved sustainability of community scale solar energy installations through community empowerment and local support. Furthermore, the fact that the present research study is establishing a data bank for social and technical issues for solar PV systems in Malawi, attaches an additional dimension to the solar PV sustainability issues in Malawi. The data bank will assist in solar PV system sustainability assessments and evaluation of current and future projects.

1.4.2 Policy Relevance

A number of case studies have revealed that solar energy can meet the needs of the rural population in developing countries. However, many of the existing rural electrification systems in developing countries fell short of expectations and do not meet the objectives. This has led to frustrations by the beneficiaries of the systems and above that the disappointments of various stakeholders. To offset such frustrations, policy makers should incorporate policies that provide a conducive environment for solar PV deployment. Of particular interest, the policy makers should look at the sustainability of off grid systems in developing countries. Given this background, it appears sensible that the study should investigate the relationship between national policy and energy requirement for rural areas. Consequently, in case of Malawi, assessment should be made of the contribution of community energy solutions to the achievement of policy targets in the Malawi Growth Development Strategy whose main theme is Sustainable Economic Growth and Infrastructure development by 2015.

1.5 List of Reports and Materials Produced in this Dissertation

1.5.1 Reports

- CRED Monthly Draft Reports (2010-2011): Reports on the Socio-Economic Impact of the CRED Project in Chiradzulu and Chikhwawa Districts.
- Draft Report on Millennium Challenge Corporation & Standard Bank 2010 High Level Power Conference held from 4th – 5th August 2010, Lilongwe, Malawi
- Piloting An Inventory for Renewable Energy Projects in Malawi, An assessment under the Malawi Renewable Energy Acceleration Programme (M-REAP), funded by the Scottish Government, Technical Report on Inventory Process

1.5.2 Publications

- D. Frame, *Student Member, IEEE*, K. Tembo, M. J. Dolan, *Student Member, IEEE*, S. M. Strachan, G. W. Ault, *Member, IEEE*: A Community Based Approach for Sustainable Off-Grid PV Systems in Developing Countries, IEEE Power & Energy Society General Meeting, Detroit, 2011.

1.5.3 Presentations to Conference and Meetings

- Tembo & Banda (2010): Sustainable Community Energy Development Solutions and Solar Power , Millennium Challenge Corporation & Standard Bank 2010 High Level Power Conference 4th – 5th August 2010, Sunbird Capital Hotel, Lilongwe, Malawi.
- Tembo & Banda (2010): Scotland Malawi Cooperation Agreement Energy Conference: Sustainable Energy Development and Solar Power Solutions, 4th April 2011, Sunbird Capital Hotel, Lilongwe, Malawi.
- Tembo & Banda (2010): Filming Interview: Social-Economic and Technical Impact of the CRED Project, 16-17th June 2011, Mwanayaya in Chikhwawa District and Malavi in Chiradzulu District, Malawi.
- Tembo & Kunert (2012): Piloting An Inventory for Renewable Energy Projects in Malawi, An assessment under the Malawi Renewable Energy Acceleration Programme (M-REAP), funded by the Scottish Government , Technical Report on Inventory Process,

MREAP 1st Programme Steering Group meeting, 11th May, 2012, Cross Roads Hotel, Lilongwe, Malawi

- Tembo (2012): What are the Innovative Energy Technologies being Developed in Africa? Transformation Technologies III: Implication for Change Africa, 11-13th July, 2012, Gaborone International Conference Centre, Gaborone, Botswana

1.5.4 Participation in Survey and Contributions

- Participated in Evaluation of Social Impacts of a Community Rural Electrification and Development: Refer to Picken (2010): Community Perspectives of a Community Rural Electrification and Development: Mwanayaya, Malawi.
- Contributing Author: Supporting Community Energy Development in Malawi, A Scoping Study for the Scottish Government, August 2011.

1.6 Methodology

A three pronged methodology was employed for this research study that includes: analytical, theoretical and practical components. One component of the study was to collect data and information from available secondary sources like official reports and surveys, books, annual reports and the internet. Another component of this research study was a field based study of two identified CRED sites (Mikolongo in Chikhwawa District and Malavi in Chiradzulu District) where solar PV performance monitoring instruments were installed and data was collected and analyzed on a monthly basis. The last component involved collection of social and economic data through the CRED Field Coordinator and authors own observation from all CRED sites. Each CRED site was given three activity log books namely: maintenance, community grouping and income generation. The data from all these activity log books was collected and analyzed in a simple excel workbook.

In order to answer questions on why rural solar PV systems have not been sustainable, a comprehensive review of solar PV deployment challenges in Sub Saharan Africa was undertaken. A number of cases have been described, analyzed and a summary of conclusions has been drawn on factors that lead to low sustainability of solar PV systems in Sub Saharan Africa based on institutional and technical challenges. The information needed for the thesis has been obtained from:

- study of literature on rural electrification and development.
- survey of policy documents, project assessments and progress reports.
- site visits and attendance of conferences has proved to be a valuable source of both academic and industrial information that has been utilized in this research study.
- a number of case studies to give qualitative information.
- analysis of reports on technical facilities for rural energy supply.
- personal case study of the CRED project gave me substantial opportunity to discuss with high profile people in the energy sector on how solar PV systems has been used to render services to the rural areas in Malawi.
- examination of documents in libraries and on line has been of much assistance. A variety of web pages, books and book sections, scholarly papers and electronic documents have been reviewed.

1.7 Limitations

This study is subject to a number of limitations. The period for conducting practical research on the solar PV system was limited. One year of data has been used to demonstrate and draw conclusion on solar PV system performance. Additionally, the secondary data for solar PV systems was not consistently found for Malawi. Also it was very difficult to get information from some organizations in Malawi. There are inadequate research data; for instance very few technical sustainability data for solar PV systems in Malawi. These limitations are important for putting this research in context but do not detract substantially from the contributions made.

1.8 Thesis Outline

The purpose of this research study is to present and assess sustainability issues of solar PV systems in Malawi and assess the performance of the panel technology (Mono crystalline solar modules) used in the CRED Community Based project in their normal /outdoor working conditions.

Chapter 1 Presents the background to this research study in relatively general terms. The chronic energy problem due to inadequate generation in Malawi is exposed and the hypothesis that solar PV technology is one of the best ways of providing alternative energy for different applications such as for social services is made. Research objectives are stated here as aiming to address the challenges associated with off grid power in developing countries through a case study Community Rural Electrification and Development project running in southern region of Malawi.

Chapter 2 provides necessary background information of energy situation in Sub-Saharan Africa (SSA). An argument is put forward that there is energy gap and deployment of solar PV systems is strongly recommended by many countries to be one of the solutions to address the energy gap however various authors echo that sustainability of off-grid power such solar PV systems still remains a major problem in Sub Saharan African region. A number of isolated case studies in Sub Saharan Africa on sustainability of solar PV systems are reviewed. The energy situation in Malawi and challenges of inadequate generation capacity are exposed. An argument is presented that the energy gap in Malawi reflects the situation in other countries within the Sub Saharan Africa region. Also an overview of policy and energy regulation, current status and application of various renewable energy sources are discussed. Besides, typical rural electrification access is summarized and the photovoltaic technology (Monocrystalline) used in the solar PV installations for Community Rural Electrification and Development project are discussed in comparison with other panel technologies. Also various models available for modelling the solar cell are discussed and the mathematical modelling equations are explained with respect to the voltage – current characteristic curve derived from the dynamics of the circuit model.

Chapter 3 gives a comprehensive discussion of sustainable energy development. The renewable sustainability framework models that are currently under test in Sub Saharan Africa are reviewed. Community based approach for sustainable system and the socio-economic impact of the Community Rural Electrification and Development project are evaluated.

Chapter 4 presents technical and socio-economic results. Key issues that emerged demonstrating solar PV sustainability with regard to roll out of the Community Rural Electrification and Development project are discussed.

Finally, **Chapter 5** summarises the main findings of the study in a bid to answer the question of low sustainability of off grid power in developing countries.

2 Chapter 2: Energy Situation in Africa and Challenges

This chapter describes the energy situation of the African continent, including its energy sources, electricity access rates, production and use, and briefly looks at the energy policy environment, against a background of interactions between energy and economic development. It concentrates on the key energy challenges facing Sub Saharan Africa, taking solar PV technology being one such example. The solar PV problems are highlighted through reviewing a number of case studies that forms the backbone of this research study.

2.1 General Overview of Energy and Trends

Energy requirements are crucial to attainment of Millennium Development Goals and accessible supply of energy is important for the sustainability of modern societies. Prolonged use of fossil fuels is currently facing a multitude of challenges: global warming, environmental concerns, depletion of fossil fuel reserves and of late, escalating fuel price rise. These problems indicate an unsustainable situation. Renewable energy is the solution to the growing energy challenges. Renewable energy resources such as solar, wind, biomass, and wave and tidal energy, are abundant and environmentally friendly. This research study argues that sustainable use of renewable energy sources such as solar PV are capable of meeting the present and future energy demands of Sub Saharan African countries without inflicting any considerable damage to global ecosystem. However, since renewable energy systems are an increasingly popular way to generate electricity, it has come with new technological paradigms like any other new technology, new challenges have emerged which are unique to the utilization of renewable energy systems. One of these challenges in particular is the development of effective monitoring technologies to compensate for the decentralized nature of remote power generation and improve on renewable energy sources sustainability such as solar PV.

2.1.1 Energy in Sub- Saharan Africa

Marrison & Larson (1997) have pointed out that approximately 1 billion people live in Africa out of the world's population of 6.7 billion. This represents 15% of the world population and accounts for 2% of world economic output. On the other hand, the United Nations baseline prediction has indicated that Africa's population is increasing at an average annual growth rate of 2.6%. The same sentiments have been shared by Blyden and Davidson (2005) who have noted that Africa's population is projected to be 1.3 billion by 2020. In this way, it is clear indication that Africa's energy demand will increase and currently there is severe shortage of energy. Evidence in support of this position can be found in several authors including Karekezi and Kithyoma (2003) & Hammond and Kemausor (2009) who have observed that only 30% of the 690 million people in Sub-Saharan Africa have access to electricity while the rest are not connected to electricity. Furthermore, electricity access rates vary considerably from urban areas to rural areas leaving the rural areas with very low access rates even though most of the population lives in rural areas. Similarly, Eberhard & et al (2008) argue that electrification access rates in Sub Saharan Africa are lower when compared to South Asia and Latin America where access rates are more than 50% and 80% of the population respectively. Also it is observed that the electricity access rates are declining and it is unlikely that Sub Saharan Africa will reach the 40% universal access to electricity by 2050. According to Davidson et al (2007) & IEA (2008) North Africa has favorable rural and urban electrification access rates compared to Sub Saharan Africa. Only 57.5% of urban and 11.9% of rural populations in SSA have access to electricity while in North Africa, 99.6% of urban and 98.2% of rural populations have access to electricity (Figure 2.1).

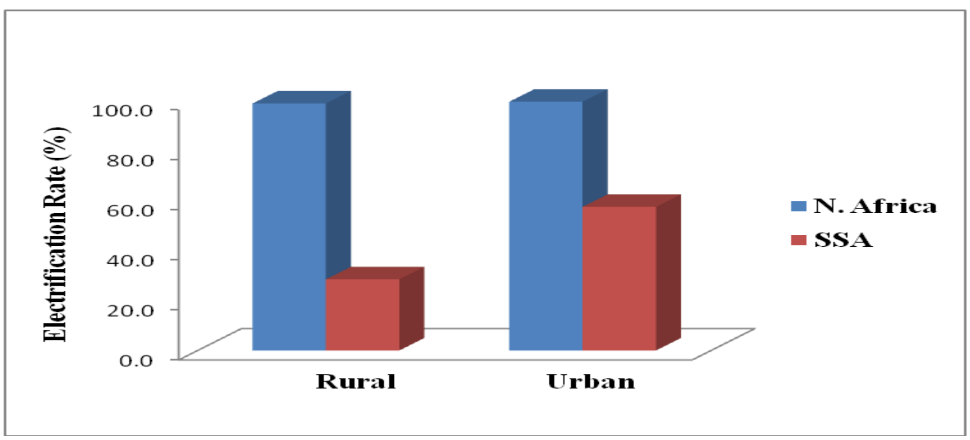

Figure 2. 1: Comparative Electricity Access Rates Between Sub Saharan Africa and North Africa. Source IEA (2008)

Although Sub Saharan Africa has low electricity access rates, by contrast there is a growing body of evidence that Sub Saharan Africa is endowed with vast resources of energy that could be harnessed to increase the electricity access rates. Moreover, Nkweta & et al (2010) have observed that the energy resources exist in two major forms; fossil fuels and renewables. For instance, Sokona (2010) noted that oil reserves estimates in the late 1980s were put at 8 billion tonnes and based on the current production rates are estimated to last close to 25 years. Similarly, The International Council for Science (2006) echoes that the proportion of the world's proven global economic recoverable oil, coal and natural gas in Africa are 9%, 6% and 7.2% respectively. In contrast, little effort has been made by oil extracting companies to search for additional oil reserves since drilling is an expensive venture.

Whilst the discussion in the preceding paragraph centred on giving an overview of the energy sources in Africa, this section aims to highlight where such energy has been harnessed and discusses the electrification levels in SSA. Substantial body of research has shown Davidson et al (2007) that South Africa is heavily dependent on fossil fuels. Coal and nuclear energy are mostly used in South Africa for industrial and utility power production, with coal contributing 50% of the total energy. Similar sentiments are expressed by Davidson et al (2007) that a wider Sub Saharan Africa depends heavily on inefficient and environmentally questionable traditional biomass which is mainly used for cooking and contributes more than 80% of primary energy. For example, various commentators including Karekezi & Kithyoma (2002); Karekezi et al (2003); Kammen and Kirubi (2008); Jumbe et al (2009) & Openshaw (2009) have approximately estimated that biomass accounts for 97%, 95%, 84% and 70% of the total national energy supply of Malawi, Uganda, Sudan and Kenya respectively**.** Furthermore, natural gas reserves are found in Angola, and the Southern and Eastern countries of Sub Saharan Africa. Davidson et al (2007) makes it obvious that out of the 6.6% of the global total of 9,771 billion cubic metres of oil for the 1991 estimates, 56% contribution comes from North African countries and the remainder is shared amongst Sub Saharan African countries, with Nigeria contributing 33%. It is clear then that there is a distinct difference between Sub Saharan Africa and the rest of Africa in terms of energy sources that have got a significant bearing to electricity access rates. A contrary explanation is presented by United Nations (2008) that the diminishing non renewable energy reserves is a wake- up call for countries in the Sub Saharan Africa to switch to renewable energy sources such as solar PV so that the current electricity energy gap can be minimized.

2.1.2 General Overview of Energy in Malawi

Having reviewed energy situation in SSA, this section looks at the general overview of energy in Malawi. According to several commentators including Malawi Energy Policy (2003); United Nations Development Fund (2003); Girdis & Hoskote (2005); Government of Malawi (2009); REEEP (2009) & Openshaw (2010) traditional biomass, which accounts for 97% of energy use in form of firewood and charcoal is widely used in Malawi for providing energy for heating, cooking and lighting in households. This use is inefficient and in some areas puts pressure on biomass resources. The authors further argue that residues from agriculture and forestry can provide major opportunities for modern energy sources in Malawi.

Furthermore, Malawi Energy Policy (2003) & Girdis and Hoskote (2005) indicate that there are other indigenous alternative sources of energy, which include coal in Malawi. It is stated that coal and petroleum based energy accounts for 5% in the energy mix. This point is also sustained by the work of Dulanya (2006) who point to the fact that Malawi has 800 million metric tonnes of coal in the Northern and Southern region of the country which could provide energy for paper mills, cement factories, agriculture and household consumption, and generation of power.

Also, Malawi Energy Policy (2003) shows that there is no domestic production of oil and Malawi meets its growing demand for oil through imports. This shows the utter dependence of Malawi on foreign fossil resource making it vulnerable to rapid and high price fluctuations. Furthermore, it is stated that alternative renewable energy sources such as solar PV, biogas digesters, geothermal, wind etc have been recognized as a viable solution for the energy needs of the population and project demonstrations have been done. However, very little attempt has been made to utilize this source of energy at large scale which could be a viable alternative source to reduce use of wood and oil for heating purposes.

Electricity in Malawi comes mainly from fossil fuels and hydropower and accounts for 3% in the energy mix. Several authors including Government of Malawi (2002); Government of Malawi (2009); Nkhonjera (2009); Openshaw (2010) & CIA (2010) have observed that 7 % of Malawians have access to electricity, of which 30 % live in the urban areas. Only 1 % of the rural populations have access to electricity and the access level in the rural areas has remained static for over 16 years.

Correspondingly, Chaurey & et al (2004); Gustavasson & Ellegard (2004); Nkhonjera (2009) & Openshaw (2010) have asserted that the electrification scenario prevailing in Malawi is the same as that of many Sub Saharan Africa countries. The electrification levels in urban and rural areas are low and the population in the rural areas has no access to electricity (Figure 2.2). Similarly, Karekezi & Kithyoma (2002) argue that one of the key reasons behind poor electrification levels in rural areas is that rural electrification is taken as a very expensive adventure by supply utilities. The dispersed populations in the rural areas render grid extension physically and economically unviable. Consequently, a large proportion of rural communities in the developing world do not have access to basic services including running water, toilets and lighting. However, Sambo (2005); International Monetary Fund (2007); Obeng & Hans-Dieter (2009) make it obvious that access to electricity is considered to be the life blood for governments and organizations. The authors further argue that electricity spurs socio-economic development leading to improved living conditions in rural and semi-urban areas and should be given utmost priority.

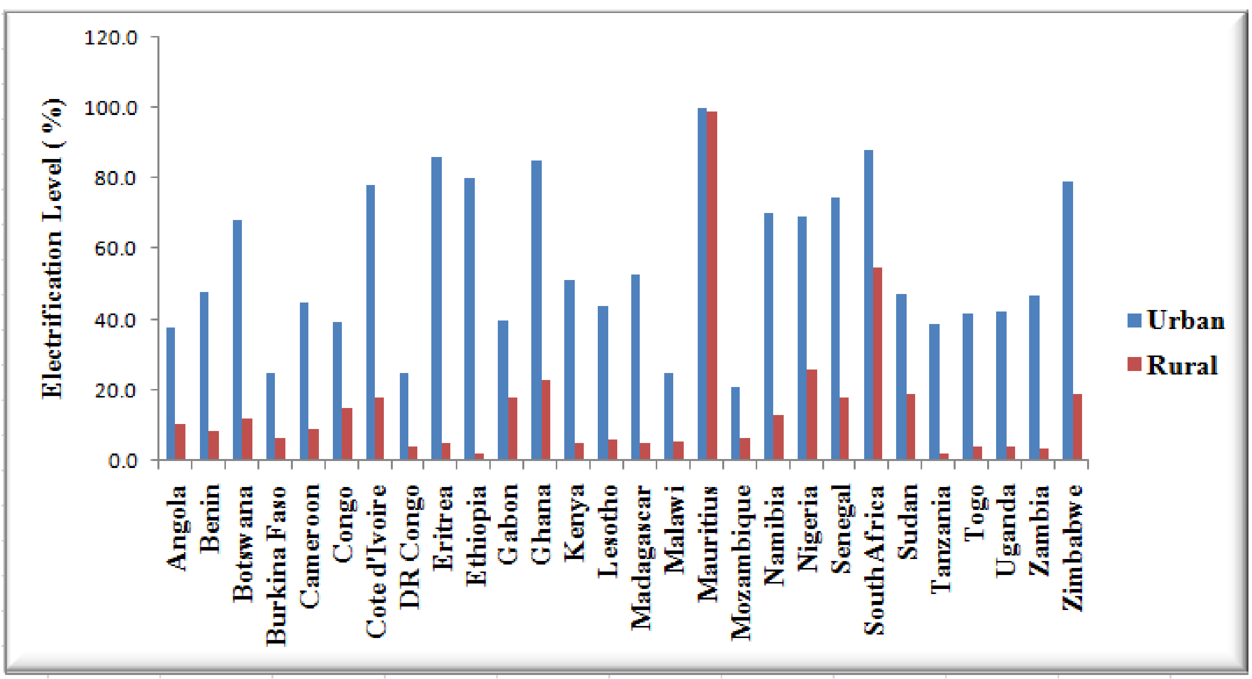

Figure 2. 2: Electricity Levels for Selected Countries in Sub Saharan Africa. Source IEA (2008)

In order to mitigate on low electrification levels in SSA, Anderson & Opok (2008) state that one of the primary objectives of the Southern African Power Pool's (SAPP) is provision of reliable and economical electricity to consumers of each of the SAPP member states. They comment that during the 1999 SAPP executive meeting, it was discussed that one of the major goals was to increase rural electrification with funding from electricity levy. However, Eberhard et al (2008) & Hammond & Kemausuor (2009) argue that there are still low electrification levels in many countries in Sub Saharan Africa; national electricity grids fail to meet electricity demand for domestic and industrial use. Furthermore, national electricity grids are plagued with intermittent power black outs and heavy load shedding programmes. Alternatively, household diesel and petrol generators provide energy for the domestic and industrial sector in normal operation but especially during grid black-out conditions. Certainly, there is no shortage of disagreement, while there is a drive to extend the grid electricity to rural areas; NEPAD-OECD Africa Investment Initiative (2009) argues that the population that lives in remote rural areas cannot afford this alternative source of energy due to their low income to meet electricity tariffs. At the same time the private sector incur extra costs acquiring their own power source. Various authors including Karekezi and Kithyoma (2003); NEPAD-OECD (2009) & Nkwetta et al (2010) have indicated that most African countries have low electrification levels as a result of suffering from significant energy losses as high as 30% exceeding the international targets of 10 to 12% due to poor management, inadequate maintenance, old electrical power equipment for generation, transmission and distribution, lack of trained personnel and illegal connections that has led to unbilled and unmetered electricity consumption. Besides, this has resulted in huge system losses and poor quality electricity that is inefficient and unreliable and giving rise to energy unsustainability. According to SADC (2009), the demand for energy is increasing at the rate of 4.6% in Sub Saharan Africa and surplus generation capacity is running out. SADC (2009) estimated that the total installed electric generating capacity interconnected to grid is 53,445 MW and out of which dependable capacity is 41,000 MW against a demand of 42,000 MW. Therefore, it is observed that there is mismatch between supply and demand, some commentators link this directly to lack of sustainable economic growth in the Sub Saharan Africa region. The above sentiments are consistent with Blyden & Davidson (2005) that energy demand in Africa is higher than supply and generation units are subjected to enormous pressure to meet high demand of electricity in the commercial and industrial sector.

Correspondingly, Okoro & Chikuni (2007) argue that efficient and reliable power supply is essential for the development of economy while on the other hand unreliable power supply leads to slow development of the country and scares away investors. They also point to the fact that aggressive power sector reforms lead to effective, efficient and responsive power supply in generation, transmission and distribution. It also stimulates private sector investment in power generation and supply and above that it enhances service reliability and efficiency amongst private companies. In agreement with the above sentiments, Mebratu & Wamukonya (2006) observed that there have been improvements to the quality of electricity service and access rates since inception of power sector reforms in some African countries. For instance, Mebratu et al (2006) specifically mentions Ghana, Cote d'Ivoire, South Africa, Tanzania and Zimbabwe amongst others where there has been reduction in technical losses and increased tariff collection levels. However, Mebratu & Wamukonya (2006) argue that in Sub Saharan Africa rural electrification was not taken into account during the inception of power sector reform and furthermore, investment in electricity generation and infrastructure has been neglected under reform. As a result, most of Sub Saharan African countries have been experiencing heavy power shortages and thereby exacerbating access gaps. There has been growing acknowledgement by Blyden and Davidson (2005); SADC (2009) & NEPAD-OECD Africa Investment Initiative (2009) that Sub Saharan Africa has failed to generate funds for the purpose of increasing the generation capacity and maintaining the existing infrastructure.

All the indications therefore point to the fact that the majority of countries in Sub Saharan Africa have been unable to invest sufficiently in energy infrastructure to support sustainable economic development. Electricity grids generally serve small fractions of the population and due to lack of investment, are unable to provide reliable quality of supply to their existing customer base. Additionally, Davidson et al (2006) have echoed that there is need to have a collaborated effort towards developing a viable energy sector by all stake holders: international bodies, Non Governmental Organizations, private sector and public sector to maximize energy efficiency since there is uneven distribution of resources.

2.1.3 Renewable Energy in Sub Saharan Africa

This section looks at the potential of renewable energy that can be utilized to provide sustainable power in Sub Saharan African region and it further gives an overall picture that in European countries renewable energy generation contributes substantially to the national energy use. Lastly it provides an overview picture that fossil fuels are diminishing world over and cannot be relied upon to provide sustainable power consequently renewable energy generation is a probable solution to meet the energy challenge in Sub Saharan African region.

The Sub Saharan Africa region has renewable energy potential that can be exploited with modern technology. According to Karekezi et al (2001) & Karekezi and Kithyoma (2003) Sub Saharan Africa has a geothermal potential of 9,000 MW and significant hydropower potential exists in many countries. Literature shows that hydroelectric potential spans from the great African Lakes to Kenya and Zambia then spreading to the Atlantic coastline from Guinea to Angola and Democratic Republic of the Congo. Sokona (2010) notes that the African hydroelectric resources are estimated at 1,383GWh/year with most of it concentrated in Sub Saharan Africa and Democratic Republic of the Congo contributing 60% of total. It is also estimated that the exploitable hydroelectric potential in Democratic Republic of the Congo is equivalent to over five times the installed capacity in United States of America. The author also makes it clear that the hydroelectric technically and economically exploitable potential is 46% and 27% respectively. Although the hydroelectric power is a potential resource, it is important to note that there are barriers in exploitation of Africa’s hydropower potential. Some of the barriers include the absence of long-term hydrologic and climatic data for effective planning, weak policy, and poor technical and environmental management. Besides, even where monitoring networks exist there is a lack of financial, technological, infrastructural, and human resources to maintain the hydropower systems once developed. However, Byden & Akiwumi (2008) argue that the hydropower developed in Africa including Sub Saharan Africa, is the lowest world-wide. Only 7% of economically exploitable potential has been developed against 75% and 69% for Western Europe and North America respectively. Additionally, studies show Karekezi & Kithyoma (2003) that a significant proportion of present electricity production could be met by baggasse-based cogeneration in the sugar industry in Eastern and Southern countries of Sub Saharan Africa region. For instance, Mauritius has been successful in cogeneration while on one hand, Kenya has made tremendous progress in geothermal energy production. Available evidence Karekezi et al (2001) shows Sub Saharan Africa has average wind speeds of 3 m/s which are substantial to generate energy to drive wind pumps for water pumping to be used in irrigation and provision of safe drinking water. According to BBC News (2008) there is existence of constantly blowing and consistently strong winds in SSA especially along the top of the rift valley, the mountain plateau which runs through East Africa from Ethiopia to Malawi and Mozambique. However, it is further argued that despite substantial wind potential, wind power is still unexploited in Sub Saharan Africa. Some of the reasons why wind technology has not been exploited include; high initial capital investment, weak and unstable local currency that tends to make imported machines expensive, there are so few working wind systems and is treated as unproven technology and lack of expertise in wind technology and lack of countrywide wind data. Conversely, it is stated by EWEA (2003) that in Europe, where the industry is well developed, the target in most countries is to generate 50% of energy through wind. For instance, Germany produces 3,000MW of power from wind turbines and in Tanzania wind turbines at Njiapanga provide 50 MW of power that contributes 10% of Tanzania's current power needs. Also, current generation of electricity through wind power in Europe is as shown in Table 2.1 below:

Country	**Wind Power Electricity Production (GWh)**	**Contribution to the National Energy Use (%)**
Spain	42,976	16
Germany	35,500	9
Portugal	8,852	18
Denmark	7,808	21
Ireland	3,473	14

Table 2. 1: Wind Potential in Selected European Countries. Source: Wikipedia (2011)

Having considered hydro power and wind potential in SSA, this section looks at solar potential and dwindling fossil fuels. It has been reported by The European Climate Foundation (2009) that each year 1 billion TWh of solar radiation fall on the surface of the earth and corresponds to

70,000 times of the world's current electricity demand. It is also stated that solar power has the highest potential of all renewable energies (Figure 2.3). For instance, only 3% of the total area covered by solar parabolic trough power plants in the Sahara Desert would be large enough to supply the world's total electricity demand. In support of the aforementioned, studies by Hammond & Kemausuor (2009) show that Sub Saharan Africa has significant solar resources in some parts of the region and solar radiation energy in many countries is above 4 kWh/m^2 per day. However, Karekezi et al (2003) notes that despite the abundance of renewable energy resource, only a fraction of this energy has been harnessed for domestic and industrial purposes**.**

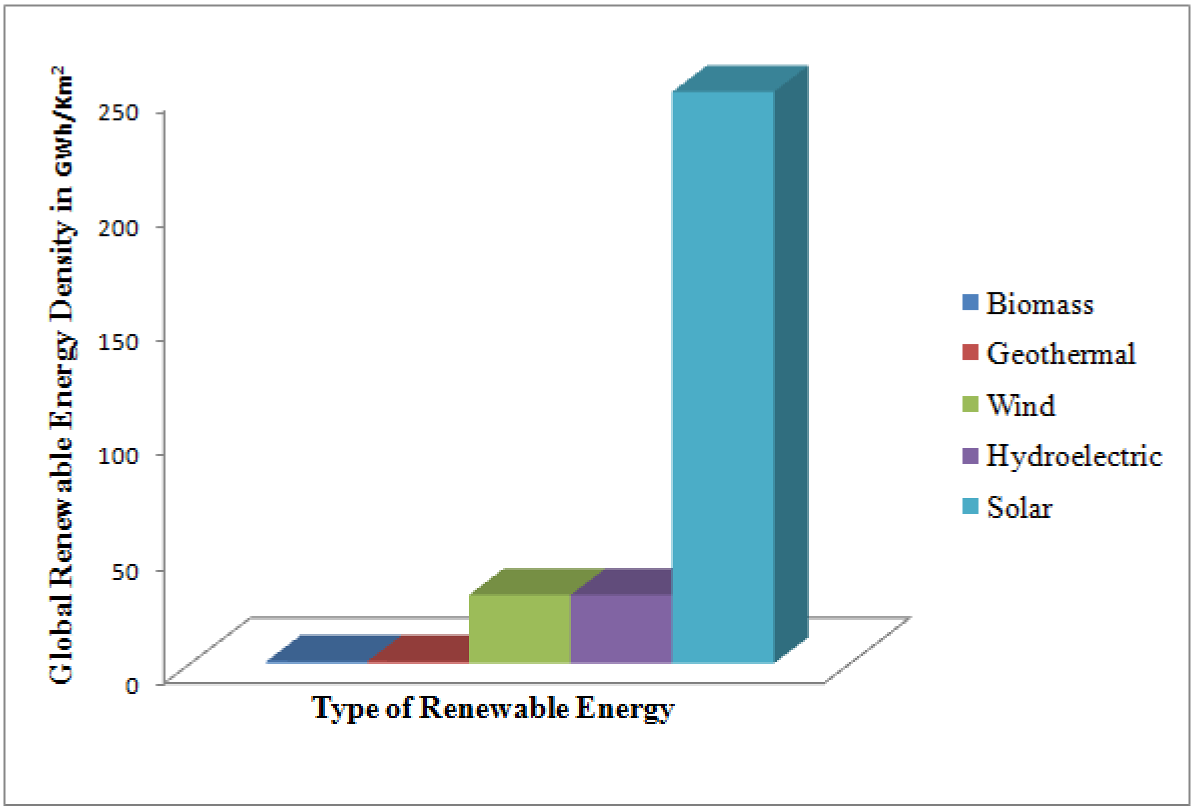

Figure 2. 3: Global Renewable Energy Densities GWh/Km^2. Source European Climate Foundation (2009)

However, Nkweta & et al (2010) argue that while a good number of developed nations enjoy secure uninterrupted power supplies with substantial utilization of renewable energy, most Sub Saharan African countries have chronic power deficiencies related to demand and under utilization of renewable resources, and in particular the abundant solar energy resource. Despite the deficiency in harnessing renewable energy resources, Wolfe (2007) argues that the general consensus in Sub Saharan Africa has been to emphasize the dissemination of renewable energy technologies in the rural areas. The author further argues that apart from being clean technologies, renewable energy option offers opportunity to significantly offset foreign exchange that is used for importing oil for electricity generation. It also indicated that since renewable energy technologies exist in modular form, they are well suited for meeting localized rural energy demand. Moreover, the European Commission (2008) states that renewable energy resources assist in meeting inadequate power supply for the rural population and at the same time address the issue of global warming consequently the main issue which is driving the increasing use of renewable energies. For instance, the IPCC (2007) assessment report noted that carbon dioxide released by the burning of fossil fuels accounts for more than half of the global greenhouse gas emissions responsible for climate change. Besides, The United Nations (2008, p37) reported that in Europe 77% of carbon dioxide emissions were energy related. In order to mitigate on carbon emissions, the United Nations (2008) is advocating the use of more efficient, 'greener' technologies and further argues that energy technologies developed today will ultimately shape the greenhouse gas emissions in the decades to come. Moreover, Zhao & et al (2009) have highlighted that the world is moving towards periods of what is known as "Peak Oil" and this is the date when half of the world's oil supplies will have been exhausted. It is not known exactly when this date will occur but it has serious implications for the development of alternative technologies. This is because when Peak Oil does occur this may signal the end of cheap oil. The above argument is further supported by evidence from Zhao & et al (2009) who argue that one concern is that as peak oil approaches, the price of oil will not respond immediately and therefore developing long term alternatives will be discouraged by the market and not initiated soon enough. Also European Commission (2008) observes that the same theory applies to coal and natural gas which are being depleted and will run out, however again it is not known when this will be. It is stated that worldwide coal reserves are expected to last between 133 and 150 years, based on current consumption levels. Identified uranium reserves are expected to last 100 years, whilst BP claim that identified oil reserves could last for 41.6 more years on current production levels. The same European Commission (2008) estimates that identified natural gas reserves have the potential to last between 58.9 and 60.3 years. Whilst work continues to identify more sources of these raw materials, these figures highlight the need to switch fast to renewable energy since the countdown is unavoidable. On the other hand, the

European Commission (2008) report shows that there is disparity of fossil fuel reserves between countries. For example, 80% of the world's coal is located within six countries, three of these are developed countries, and South Africa, China and India make up the rest. Also 2/3 of the world's oil supplies are in the Middle East. This leads to the fact that renewable energy technologies will be a viable solution to mitigate on green house gas emissions and at the same time address the problem of energy deficiency.

In summary all the above indications show why renewable energy in Sub Saharan Africa is getting such high profile attention. It is associated with provision of sustainable power, reduction of global carbon dioxide and increasing electricity access rates to the rural poor. Moreover, the long-term nature of renewables would allow a more gradual and less disruptive transition away from dependency on fossil fuels. This viewpoint is further sustained by some evidence indicating that at the global level, the medium-term outlook for fossil fuels demand may not be as high as previously anticipated due to concerns over associated negative environmental impacts. In the long-term, fossils fuels may also become less competitive in cost as reliance on more costly oil reserves grows and alternative energy systems such as fuel cells become more affordable. As a result, many commentators including Chaurey & et al (2004); IIskog (2008); Houghton (2005) & Bawakyillenuo (2007) believe that renewables constitute a reliable and ecologically sound long-term alternative for virtually all African countries including current oil-exporting nations, many of which have abundant and unexploited biomass, hydro, solar and wind resources. In addition the authors argue that the reason behind this is, the international bodies are supporting energy development in Africa don't want to add to the carbon dioxide issue by encouraging the building of Coal and Gas power stations. It is against this background that this research study argues that renewable energy sources have the potential to solve Sub Saharan Africa energy problems and attract development support. This is the case because the ability to promote a clean power source and improve basic living standards is the major attraction for the international funding of renewable energy such as solar energy in developing countries.

A further argument put forward in this research study is that the adoption of renewable energy as an alternative source of energy has driven many governments to incorporate renewable energy in their policies in order to address the gap of energy needs for the bulk of rural population through the use of renewable energy sources such as wind, solar PV, biomass, geothermal etc.

Consequently there are major reforms in the power sector that include reviews on energy acts and policies in order to improve energy supply efficiency and accelerate rural electrification. At the same note, IIskog (2008) echo that this has resulted into new institutional arrangements. A classic evidence is given by many authors including Government of Malawi Energy Policy (2003) & IIskog (2008) that energy policy documents of many Sub Saharan Africa countries single out solar PV systems as one of the many renewable energy technologies that provides a solution to the growing energy challenges in Africa because it is environmental friendly, cost effective, accessible, stand alone and suitable for African rural communities which are homogeneous. Consequently, the third argument in this research study singles out solar PV amongst renewable energy sources being an important part of renewable drive although not problem free. Therefore, there is a deliberate inclusion of proactive and long term policy oriented renewable energy (solar PV) programmes in the policy documents of most Sub Saharan African countries. However, Karekezi (2001) argue that for such programmes to have impact on the rural population, the policy programmes should be designed to demonstrate the economic and environmental benefits of renewable technologies to the rural poor. For example job creation and income generation.

To encourage support for adoption of solar PV technology, many authors including Duke & et al (2002) & Boccaletti et al (2008) point to the fact that solar PV systems is well suited where electrification levels are low. It is argued, for example, that solar water pumping has great advantages over conventional systems as diesel or propane engines require not only expensive fuels, but are also are noisy and pollute the air. Further insights of the importance of solar PV technology for rural Sub Saharan Africa are given by the work of Karekezi & Kithyoma (2002). The authors argue that solar PV technology is the most attractive option of the renewable energy and many national renewable and rural energy strategies have often given priority to the deployment of solar PV technology. However, Karekezi & Kithyoma (2002) literate that solar PV system has its own disadvantages despite the fact that the technology is viable. It is argued that solar PV technology has high reliance on imported components for system sustainability and deployment. Over 50% of system components are imported resulting into additional load to foreign exchange reserves. In conclusion, the authors advocate a strong emphasis on deployment of solar PV system for lighting purposes and giving a greater prominence to a wider range of renewables that offer more attractive opportunities for income generation and job creation.

Another counter argument about the suitability of solar PV as an alternative energy source is supported by evidence from Wolfe (2007) who cite that solar PV systems are expensive and has limited application despite it is an answer to addressing the problem of energy gap. Also it is difficult to make minor increment changes to solar PV systems. Moreover, any increment in electrical loads would require additional system components such as batteries, modules etc. in order to match with demand. The cost of expanding the system is transferred to the end user and most of the rural families would not be able to pay for the cost of expansion.

The accumulated body of literature above illustrates that solar PV system is a good option for rural electrification however it may only be in certain applications and that micro-hydroelectric generators, wind turbines, biomass combustion, tidal wave etc can be equally important and suited for rural energy needs. For example, renewable source of energy as outlined above can be utilized to provide water pumping, irrigation and shaft power for processing agricultural produce and increase its value thereby improve economic development and thereby spur social development amongst the local communities.

2.1.4 Solar PV Contribution to Millennium Development Goals

This section gives a brief background formation on the Millennium Development Goals. The links between energy and Millennium Development Goals are discussed in meeting sustainable social and economic growth in the remote rural communities.

Over a decade ago, the United Nations Millennium summit was held and the international community adopted the Millennium Declaration and Millennium Development Goals (MDG) as strategic indicators by poor and donor countries to measure progress towards reducing extreme poverty and improving quality of life. Following the Millennium declaration, poor countries were strongly encouraged to adopt the MDGs in their Poverty Reduction Strategy Papers. Consequently, United Nations (2008) & Episcopal Church (2008) observed that 190 countries worldwide signed up to Eight Millennium Development Goals in the Millennium Declaration in the year 2000. This declaration would act as a framework for international development activity. It was envisaged that in signing this agreement countries agreed to work towards rescuing people who are in “extreme poverty” as called by United Nations. The deadline for achievement was set for 2015 and the world has passed the midpoint. Assessment at the half point in 2008 reveals that progress in achieving MDGs is mixed and slow, particularly Sub Saharan Africa that lags on all MDGs. For example, new data on poverty show that, China reduced the incidence of poverty from 60% in 1990 to 16% in 2005 while Sub Saharan Africa during the same period reduced poverty incidence from 58% to 51%. However, World Bank (2009) argues that despite the decrease in poverty incidence, absolute number of poor people in Sub Saharan Africa rose from 296 million to 388 million. On the other hand, the World Bank (2009) makes it clear that Sub Saharan Africa has made relatively little progress on health. For instance, while Sub Saharan Africa accounts for 20% of the world's children, 50% of these die before the age of five. Also Sub Saharan Africa has high maternal mortality ratio of 900 deaths per 100,000 births. According to World Bank (2009), it indicates that health issues are linked to lack of access to safe water, lack of mother's education, malnutrition, lack of reliable energy and above all slow economic growth. In collaboration with the World Bank, studies by Cabraal et al (2005) have documented that productive use of energy has a significant role to play in achieving MDG goals related to income and poverty, education and gender issues. The authors argue that productive uses of energy in rural areas are linked to greater economic growth, increased rural productivity and opens opportunities for employment. For instance, electricity would provide motive power to drive agricultural based industries and power farm machinery consequently modernize the agricultural sector. And the modernized farms would provide inputs to large commercial enterprises such as rural cooperatives sugar factories. Furthermore the authors make it clear that electricity has significant potential to provide the driveshaft power and lighting that is suitable for rural industries. This research study argues that energy requirement underpins the Millennium Development Goals. Improving this is core to the Governments of Sub Saharan Africa poverty reduction and development strategy. For example, successful experiences on the study of the impact of solar home systems on rural livelihoods Gustavasson & Ellegard (2004) from the Nyimba Energy Service Company in Zambia in 2000 had shown that electricity is related to education level and report that 58% of the students in their study increased the number of reading hours after the installation of solar electricity. Another more recent study by (World Health Organisation (2005); Sharma (2007) & World Health Organisation (2008) points to the crucial emerging lesson of the relationship of solar electricity and health. It is argued that indoor air pollution which is a result of inefficient burning of firewood and biomass in rural homes has an impact on both morbidity and mortality. Consequently unhealthy people work less efficiently than healthy people, while on the other hand improved health lead to higher incomes. And it is specifically highlighted by Cabraal & et al (2005) that the growth of individual incomes is a prerequisite to opening opportunities to receive basic education, health care, freedom of entertainment and freedom to participate in the labour market. With available evidence above, it is quite obvious that any discussion of energy development in Sub Saharan Africa needs to consider the context of the MDG's. This wide ranging international declaration targets the eradication of extreme poverty and provision of quality life in education and health just to mention a few. Also, the MDG's do not specifically target energy development, however commentators including Cabraal et al (2005) have acknowledged that provision of reliable energy is as one of the underpinning pillars in achieving the targets because it contributes greatly to improving living conditions around the world. It is argued that energy access has substantial positive impact on rural growth and livelihoods, economic development through improved productivity as a result of income generating activities and improving women's empowerment. Cabraal & et al (2005) further argue that impacts that are linked to improvement of the livelihood of the population through productive use of energy are linked to the achievement of Millennium Development Goals. Cabraal & et al (2005) & IEA (2008) conclude that an energy technology or energy policy has the power to influence a specific selection of Millennium Development Goals and their respective targets. It is indirectly crucial to satisfying most of the Millennium Development Goals. In addition, the authors specifically mention solar PV system being amongst the key technological option that is linked to provision of lighting, pumping for irrigation and reduction in the carbon dioxide emission thereby improve the quality of life for rural dwellers. Moreover, there is growing evidence that solar PV systems stimulate economic development by engaging people in harnessing energy and providing energy services. Several reviews including Mukukatin et al (1994); Karekezi et al (2003) & Obeng & Hans-Dieter (2009) have examined the available evidence linking the ability of solar PV system to assist in alleviation of poverty through income generating activities, improve quality of education, and health. In agreement with several authors above, this research study argues that solar PV is well placed to contribute to the Millennium Development Goals and furthermore, Flavin & Aeck (2005) & Cabraal & et al (2005) highlight that the associated targets which have been identified as being most likely to be impacted by renewable energy technologies such as solar PV system are shown in Table 2.2 below:

Technology/Fuel Type	Millennium Development Goal	Steps Toward Goal	Modern Energy Contributes by
Grid: Fossil/renewables Minigrids: Diesel generators Small hydro Small wind Biomass—combustion/ gasification Hybrid–diesel with PV/wind/biomass Stand alone systems: Solar PV Biogas Diesel generators Microhydro Shaft/mechanical energy: Wind Water wheels Heat energy (community scale): Biogas Biomass—combustion/ gasification Solar thermal Heat energy (household scale): Liquefied petroleum gas Biogas Solar thermal Passive solar design	1. Cutting Extreme Poverty and Hunger	• Reduce by half the proportion of people living on less than $1 a day • Reduce by half the proportion of people who suffer from hunger	• Reducing share of household income spent on cooking, lighting, and space heating. • Improving ability to cook staple foods. • Reducing post-harvest losses through better preservation. • Enabling irrigation to increase food production and access to nutrition. • Enabling enterprise development, utilizing locally available resources, and creating jobs. • Generating light to permit income generation beyond daylight. • Powering machinery to increase productivity
	2. Universal Primary Education	• Ensure that all boys and girls complete a full course of primary schooling	• Providing light for reading or studying beyond daylight. • Creating a more child-friendly environment (access to clean water, sanitation, lighting, and space heating/cooling), which can improve attendance in school and reduce drop-out rates. • Providing lighting in schools, which can help retain teachers • Enabling access to media and communications that increase educational opportunities. • Reducing space heating/cooling costs and thus school fees.
	3 Gender Equality and Women's empowerment	• Eliminate gender disparity in primary and secondary education preferably by 2005, and at all levels by 2015	• Freeing women's time from survival activities, allowing opportunities for income generation. • Reducing exposure to indoor air pollution and improving health. • Lighting streets to improve women's safety. • Providing lighting for home study and the possibility of holding evening classes
	4,5, 6 Health	• Reduce by two-thirds the mortality rate among children under five • Reduce by three-quarters the maternal mortality ratio • Halt and begin to reverse the spread of HIV/AIDS • Halt and begin to reverse the incidence of malaria and other major diseases	• Providing access to better medical facilities for maternal care. • Allowing for medicine refrigeration, equipment sterilization, and safe disposal by incineration. • Facilitating development, manufacture, and distribution of drugs. • Providing access to health education media. • Reducing exposure to indoor air pollution and improving health. • Enabling access to the latest medicines/experti se through renewable-energy based telemedicine systems.
	7 Environmental Sustainability	• Integrate the principles of sustainable development into country policies and programs; reverse loss of environmental resources • Reduce by half the proportion of people without sustainable access to safe drinking water • Achieve significant improvement in the lives of at least 100 million slum dwellers, by 2020 management.	• Boosting agricultural productivity, increasing quality instead of quantity of cultivated land. • Reducing deforestation for traditional fuels, reducing erosion and desertification. • Reducing greenhouse gas emissions. • Restoring ecosystem integrity through land

Table 2. 2: Importance of Energy to Achieving Specific Millennium Development Goals. Source: Flavin and Aeck (2005) & Cabraal et al (2005)

2.1.5 Sustainability Scenario of Solar PV Systems in Sub Saharan Africa

The main thrust of this section is to review solar PV sustainability issues in Sub Saharan Africa. It begins by highlighting that solar PV has the capacity to meet various electrical applications. It then reviews solar PV projects in selected Sub Saharan African countries as case studies. The review is significant because it informs the research study and it uncovers the dynamics of rural electrification through solar PV and the on-going discussions on sustainability of solar power by various commentators.

Available evidence Karekezi (2003) shows that solar PV is becoming increasing important in achieving the Millennium Development Goals in provision of energy for water pumping, lighting, vaccine refrigeration, water treatment, telecommunication and many other applications and above all addressing the chronic deficiency in energy in Sub Saharan region. However, a contrary explanation is presented by Wolfe (2007) & Karekezi & Kithyoma (2002) who argue that despite the many applications of solar PV as mentioned above and the enormous drive and considerable levels of investment, solar PV projects are prone to failure. Consequently, some of the prevailing challenges that affect sustainability of solar PV in Sub Saharan Africa are highlighted in the case studies below:

2.1.5.1 Case Study 1: Mutale Local Authority in South Africa

A number of pilot solar PV system projects received widespread attention in Sub Saharan Africa, such as Mutale Local Authority in South Africa where a pilot project was commissioned to provide off grid electricity to 582 households residing in Folovhodwe village. The pilot project was undertaken to demonstrate that solar PV systems can be adopted as viable option to provide rural electricity services in Africa. However, not all went well with this solar PV project. The project faced many operational problems, mainly with failure of components such as charge controllers, batteries and lights. In addition improper planning and implementation, lack of maintenance skills contributed significantly to low sustainability of the project. Literature shows Bikam & Mulaudzi (2006) that out of 582 solar PV systems that were installed between 1998 and 1999, only 13 were in good working condition, 20 solar PV were stolen and 549 solar PV systems were not in good working conditions by the middle of 2004. The statistics clearly shows that the number of solar PV systems that had broken down was higher than the ones that were in good condition by 2004. In conclusion, the authors cite that the project was a total failure during the implementation for a number of reasons as listed below:

- The project planners grossly underestimated to deploy six technicians to manage 549 solar PV systems and no plans were put in place to train more technicians. Consequently it overstretched working capabilities of Technicians. This meant that Technicians were forced to attend for minor faults which the local community would have done on their own if they were trained.
- The local community was not trained on the basic maintenance skills of their solar PV. For example the end users were not taught how to properly operate and repair faulty equipment because it was not built into the planning and implementation stages of the project
- Security of the equipment was not taken into account consequently 20 solar PV systems had broken down due to the fact some parts of the system were stolen. The project initiators did not foresee the problem of theft of materials, problems related to the procurement of spare parts and who would bear the cost of maintenance of the facilities.
- Most of the local people were unable to pay the maintenance fee of the project due to lack of funds consequently affordability in terms of operational costs was not taken into account at the inception of the project. Also this resulted in lack of available funds to maintain the solar PV system.
- The failure of the project was also related to the inability of the policy makers to tackle the question of the role that each stakeholder should play to ensure the success of the project in a rural setting. For example, private sector participation at the inception of the project to ensure that the objectives of the project were met and the project was financially sustainable

Correspondingly, the experience of the Mutale Local Authority project are further confirmed by the work of Niewenhout & et al (2001) and they argue that despite high initial installed cost of solar PV systems, in many occasions the service and maintenance costs are not taken into account at the inception of the solar PV systems installation. Moreover, the authors argue that apart from technical and organizational problems on the deployment of solar PV system in Africa, financial problems appear to present a huge barrier to the growth and sustainability of PV systems and the case study of Mutale Local Authority in South Africa demonstrate that shortfall.

Also they state that over the years, studies have shown that there is little data on real maintenance costs of solar PV systems.

2.1.5.2 Case Study 2: Limpopo Province and Easter Cape

The project involved installation of pre-paid solar system with battery storage. The aim of the project was two-fold: (i) to contribute to social and economic development amongst the rural population and (ii) promote rural electrification. However, Mabuza & et al (2007) argue that the Solar Electrification by the Concession Approach in Limpopo Province and Eastern Cape in South Africa met many challenges because it did not incorporate local community needs and expectations at its inception. The project had deployed 6,000 Solar Home Systems by the end of March 2000 however 1,400 SHS were repossessed by Shell-Eskom due to default payment by the users. It is argued that the project failed in the following areas:

- There was no proper communication on the loading capacities of the SHS to the end users. The SHS were designed for lighting only however the users wanted to use the system for cooking as well. This led to end user dissatisfaction consequently many users were not willing to continue paying for the energy provision that was limited in its use.
- Skills transfer was not incorporated in the design of the project. For example users could not even replace a bulb once it burnt out.
- Use of punitive cost recovery methods for those low income people who have defaulted payment for electricity use.

2.1.5.3 Case Study 3: UNDP/GEF Solar Energy Funded Project in Zimbabwe

In 1992 UNDP/GEF a solar project was approved for funding in Zimbabwe with a number of aims encompassing the enhancement of long sustainability of PV system. Furthermore, Mulugetta & et al (2000) state that the project was concerned with uplifting the quality of life for the rural people and to mitigate on the effects of carbon dioxide emissions. The project targeted to install more than 9,000 SHS of 45 Wp in rural homes, health centres and schools by the end of 1997. Also, the authors state that upon assessment of the project in the year 2000, it was found that the project had managed to deploy more than 2,000 SHS in different rural areas in Zimbabwe. However, there were no records to show how many systems were still working during the time of assessment. Therefore it raised a lot of questions about the success of the project if the project planners were unable to verify the number of SHS still working and those not working. In other words, the projects' aim was defeated by failing to account for working and non-working SHS. However, Mabuza & et al (2007) argue that a holistic approach in deployment of the rural energy needs should be taken into consideration if sustainability of the projects is to be achieved. Additionally, they highlight that the project faced a number of challenges that grossly affected the sustainability in the following areas:

- Dwindling numbers of companies that provided solar equipment from the time of inception of the project and to the time when the project was winding down. Records show that at the time of inception of the project 60 companies supported the SHS by supplying spares for the SHS but the number went down to 15 when the project was winding down. This meant that rural people could not easily find ready spares on the solar market for the maintenance of their SHS consequently sustainability of the SHS was at stake and negatively affecting the objective of stimulating a vibrant rural solar market growth to support the SHS.
- There was limited information relayed to the end users on the loading capacities of their SHS. For example, the people were using the SHS for longer hours than what the system could manage and also end users demanded an increase in their load without increasing the number of panels. Also, the authors argue that the SHS were not properly installed in the rural areas due to the haste in which they were deployed in order to meet the installation target.
- The project was not properly managed due to under staffing consequently inadequate quality controls on the installed systems. The available staff was overstretched to properly manage a vast SHS located in different parts of Zimbabwe. Additionally, the training skills sessions were in adequate due to staffing problems.
- There was delayed maintenance of the SHS after the customer reported problems with their systems. Approximately 20% of the system faults were repaired within one month and 30% were repaired after three months. The authors argue that distance between end users and the system installers affected the fast response to systems faults because most of the companies were based in the city.
- All subsidies negotiated by the project fell away after the end of the project and the cost of installations rose sharply.

2.1.5.4 Case Study 4: Southern Bottlers Solar Driven Beverage Coolers Project in Malawi

Having considered case studies in some parts of SSA, it is also reasonable to look at some case studies in Malawi. In Malawi available evidence United Nations Development Fund (2006) & Energy Policy (2003) have shown that 50% of the solar PV system projects have failed within few years of their inception. For instance, the Malawi Energy Policy (2003) document shows that 5,000 solar PV systems were installed in Malawi by the end of the year 2000 but only half of these were in good working conditions within two years of their operational time. Similarly, the operational problems associated with solar PV systems are found in the solar PV project run by Barrier Removal to Renewable Energy in Malawi (BARREM) in conjunction with the Department of Energy over a decade ago. The solar PV project was initiated to drive Southern Bottlers beverage coolers in the remote areas of Malawi. The BARREM report indicates that SOBO was entrusted with the obligation of involving certified solar suppliers to install, commission and maintain the systems. The whole aim of the project was to demonstrate the viability of using solar PV technology to provide beverage cooling in remote areas of Malawi. In addition to provision of beverage cooling, the project had two inherent aims, namely: (i) it was a trend to move away from using gas operated coolers which produce harmful emissions (ii) to provide lights allowing extended hours of operation and contributes greatly to rural electrification. Approximately, 2,000 solar coolers were earmarked to be deployed in the rural areas over a period of five years starting from the year 2000. However, Southern Bottlers reduced the number of coolers to 350 and by the end of the project assessment in 2005; only 6 solar beverage coolers were installed. The report highlights that the BARREM management team took long time to establish a clear strategy on how the SOBO project would roll out and be replicated. The report shows that while installations of coolers were supposed to commence in the year 2000, all the 6 coolers were installed in 2003 and were the only coolers installed by BARREM project until the project end life in 2006. Moreover, the BARREM annual project report shows that there was no commitment from Southern Bottlers to replicate the solar beverage coolers. Also, the United Nations Development Fund (2006, p 46) has reported that since then Southern Bottlers has not been aggressive on the project and no explanations have been made on whether the project was viable or not. Furthermore, the report states that what seems to have hampered the Southern Bottlers project was lack of SOBO to take ownership of the project. Also they were concerns that once the project rolled out in large scale, maintenance of the systems would be a problem since it could require a dedicated maintenance team for each site where solar driven coolers have been deployed. Hence, in the absence of the maintenance team in these sites, the solar driven coolers would not have been sustainable.

Correspondingly, United Nations Development Fund (2006) states that the BARREM survey report had shown that solar PV projects meet a lot of challenges in Malawi. For instance the report cites solar PV project at Eswazini in Mzimba district met a lot of operational problems. The BARREM report specifically mentions lack of continuous supply of spares for the maintenance of the solar PV system; poor maintenance skills and inadequate follow up by installers to assess on how the solar PV system was operating were amongst some of the reasons that threatened the sustainability of the project.

2.1.5.5 Case 5: Thyolo Solar/Wind Power Project in Malawi

The GoM initiated a MK50 million solar and wind project at Savala Village in Thyolo district in the southern region of Malawi. The project commenced operating in 2008 and the hybrid system comprised of three turbines, 50 solar panels and 140 batteries with 200AH capacity each. In addition, the system had a total installed power capacity of 20kW and was designed to provide electricity to 150 households with five hours a day of electricity usage. However, Malawi News (2012, May 6, p 5) reported that the system had experienced frequent equipment breakdowns consequently leading to reduction in capacity of generated power. For instance, wind turbines and a number of batteries got damaged hence currently reducing the number of hours for electricity usage by two hours than it was four years ago. It is also stated that the system had broken down for a number of reasons as listed below:

- Lack of well planned repairs and maintenance schedules for the system. It is said that the contractor who installed the hybrid system only came twice to maintain the broken down equipment in a time span of four years despite the frequent equipment breakdowns.
- There was no proper communication on the loading capacities of the hybrid system to the end users. It is reported that the system was designed to provide power for lighting. Besides, the system design incorporated one socket outlet in each household to provide power for radios, television and phone charging. However, it is reported that some users were connecting appliances of higher rating direct into the system. This resulted into frequent tripping of the circuit breakers due to overloads.

- Poor quality of system equipment was used by the contractor to install solar/wind power at the inception of the project. This contributed greatly to the breakdowns of the system components.
- Carelessness of the users in operating their system. The end users would switch the power unnecessarily thereby draining the stored power faster and sometimes cause the system to fail.
- Since the electricity usage was free, the planners of the project had put aside maintenance funds for the system at design stage however due to financial fraud, it is reported that the project was left without maintenance funds. Therefore it was difficult for the local people to organize funds on their own in order to purchase replacement batteries and even clear minor component failure such as replacing burnt bulbs.

2.1.5.6 Case Study 6: Rural Botswana Pilot Project

The above sentiments are consistent with Ketlogetswe & Mothudi (2008) who argue that energy policies should focus on provision of rapid and effective development of the use of solar technology power generation systems in rural communities. For example, in early 2002 the Government of Botswana and Japanese International Cooperation Agency (JICA) implemented a pilot project to assess the socio-economic merits of solar PV systems in three remote rural villages in Botswana. The project was programmed to run until December 2005. The fee-for-service model was adopted and Botswana Power Corporation was entrusted to monitor and collect revenue from the three villages that consisted of 114 Solar Home System (SHS) installations. However, literature reveals Ketlogetswe & Mothudi (2008) that due to high default level, many SHS were repossessed by the Energy Affairs Division before August 2005 because participants could not afford to make regular payments. The authors attribute this to low income status of the participants in the three villages. However, it can be further argued that in most African countries, Malawi inclusive, lack of income and finance mechanisms to the rural poor has been a major barrier to sustainability of solar PV systems.

2.1.5.7 Case Study 7: The Millennium Village Project in Malawi

In 2004 the Millennium Project was introduced to Malawi at Mwandama in Zomba District with an objective of reaching the rural poor and assist in implementing the Millennium development goals through science based community intervention. The project developed a participatory approach to ensure that the local people participated in LED Lantern pilot project which was based on market approach. Moreover, the project aimed at promotion of the use of solar products as a means of today's clean technology. Above all, the project aimed at imparting technical and economic skills on the rural population to enhancer sustainability of the project. Available evidence shows United Nations Development Fund (2006); Kammen & Kirubi (2008); Barnes & Foley (2004) & Adkins & et al (2010) that on overall, the project achieved significant results. The LED Lanterns proved to be very efficient in provision of light to the people at equal or lower costs than kerosene fuel based alternatives in Mwandama. For example, on average the cost of using LED Lantern as a source of lighting for a household was USD 29.78 per year compared to using kerosene USD 47.06 year. Furthermore, the project provided local people to engage in income generating activities and undoubtedly improved their livelihood and welfare. Although there has been significant success on the MVP, the authors' question whether the vendors and cooperatives will thrive in the medium or long term due to saturation of the market, lack of locally based suppliers for components (e.g. batteries) and inappropriate finance mechanisms (cash on delivery).

These case studies illustrate the factors contributing to the failure of solar PV systems in Sub Saharan Africa and have also demonstrated that the establishment of long-term sustainable PV projects in developing countries primary depends on building appropriate finance mechanisms, institutional frameworks, proper policy guidelines, private sector participation and capacity building which takes into account training of institutional staff, technicians and beneficiaries of the solar PV project. This research study argues that when developing a solar PV systems project, it is vital that an informed choice on the implementation model is made since an inappropriate approach to the deployment of solar PV systems will result in a failure to develop a sustainable solar PV project as the case studies above have illustrated. Also, a summary of the problems encountered are shown in Table 2.3. This research study argues that for the solar PV project to be sustainable there is need for some quantitative data on costs and benefits to provide information for sustainability analysis which will provide a base for project monitoring and evaluation phase. Therefore, the Community Rural Electrification and Development project model will be tested in order to find out to what extent it can address some of the solar PV system challenges outlined in Table 2.3.

Serial No.	Description of problem	Remarks
1	Lack of proper policy guideline at design and implementation stages	This is crucial for technology output to incorporate needs and expectations of the local community. e.g. beneficiaries could opt general application of the technology for water pumping rather than lighting alone.
2	Lack of maintenance skills of project beneficiaries	Project beneficiaries rely on the services of the technicians and cannot perform any of the service tasks for themselves e.g. replacing a bulb
3	Theft and vandalism of equipment	Gradual process to change the mindset of the local community
4	Lack of research to develop a business model specific for the technology	Improvement of income generation so that funds can be ploughed back into the system maintenance
5	Lack of spare parts	Long delays in spare part acquisition since they are ordered from abroad and severely affecting maintenance schedules
6	Lack of private sector participation	These are needed to operate, maintain and build local solar PV manufacturing industries
7	High default payment for fee for service solar PV systems	Inadequate funds generated for maintenance
8	Lack of appropriate finance mechanism	All forms of electricity generation require financial resources and management, and operational structures to remain sustainable.

Table 2. 3: Summary of Problems Contributing to Low Sustainability of Solar PV System in Sub Saharan Africa

With reference to Table 2.3, it has been observed that most of the solar PV equipment in SSA is sourced from European countries and shipment of such equipment takes long time to reach required destinations. Also the scarcity of foreign exchange has even made the procurement process of such equipment more difficult because organizations/ institutions and the private sector involved in the renewable energy sector have to wait for months before their procurement documents are processed by the banks. This has made further delays for renewable energy equipment to be delivered by overseas suppliers. In such circumstances, installers resort to purchasing poor quality renewable energy equipment available on the market stocked by un reputable local suppliers. Moreover, the equipment is not only of poor quality but expensive to procure as well. Therefore, the solar PV systems fail to remain sustainable because of the absence of spare parts and poor quality of materials used for repair and maintenance of the broken down systems.

2.2 Energy Situation in Malawi

This section reviews Malawi’s power supply. It looks at problems and constraints to progress. Moreover, the section looks at proposals that the government has put down to overcome problems and constraints of power supply.

2.2.1 Electricity Supply in Malawi

The energy supply sector in Malawi is comprised of five principal components: electricity, liquid fuels and gas, coal, biomass and other renewable energy sources. There is also, however, a further point to note that electricity supply is through mainly three major forms namely; electricity generation by hydro (94%); thermal and solar PV systems share the remaining 6%. Also Energy Policy (2003); Government of Malawi (2002) & REEEP (2009) indicate that electricity supply consists of the national interconnected grid and off grid systems in Malawi. Electricity Supply Corporation of Malawi Ltd. (ESCOM) which was established in 1957 dominates the supply of electricity. Various authors including Karekezi & Kithyoma (2003); National Statistical Office (2008) & Government of Malawi (2009) have confirmed that ESCOM’s 94% installed capacity is generated from hydropower sources that are largely cascaded along the Shire River which is fed by Lake Malawi. Until today, hydropower generation still remains the largest component and contributes 304 MW out of a total national installed capacity of 355.3MW. The demand is about 267 MW and is perceived as a suppressed demand. And the forecasted annual growth rate in demand has been averaging 6% to 8% over decades. According to Millennium Challenge Corporation (2010) concept paper (2011-2016), it is projected that Malawi will require 478 MW by 2015 and 757.4 MW by 2020.

An accumulated body of evidence Mnella (2007) & UNDP (2008) indicates that generation of power in Malawi through hydropower has not been impressive and the future looks bleak for the sole company (ESCOM). Over the years the generation capacity has been greatly affected by persistent droughts and sedimentation resulting from erosion in the catchment areas exacerbated by poor and unsustainable agriculture practices, deforestation and noxious weeds such as water hyacinths. As demand has outstripped supply and is not adequately met, power blackouts have been a common problem in Malawi throughout the year. This tends to be worse during the rainy season when silt and mud interfere with the operations of the machines resulting in constant breakdowns. For instance, Dulanya (2006) state that in 2003 ESCOM’s generating capacity was reduced to as low as 60 MW out of a total installed capacity of 240 MW. Evidence in support of this point can be found in Government of Malawi (2006) & UNDP (2008). They assert that power supply in Malawi is unreliable and has negatively affected the economic growth. Also, Adkins & et al (2010) & Malawi Daily Times Newspaper (2011; Appendix 1) have observed that the shortage of electricity is severely and its effect in Malawi is evident through extreme load shedding which is taken as means of managing the situation and this has resulted in denying the already scarce power to 93% of the population. Consequently, industries are severe hit by rolling blackouts so much so that it is difficult for industries to have sustained and optimal production of vital products which may even substitute imports. The major reason is that production flow is constantly interrupted by intermittent switching off of equipment. Moreover, the intermittent power blackout has resulted into loss of equipment and huge costs are incurred to repair the damaged equipment due to power fluctuations. Available evidence Nation Online (2013, May 8) indicates that ESCOM power supply has scared and disappointed some potential investors in Malawi. Indeed, a classic example is the failure of ESCOM to guarantee supply of adequate power to Paladin (Africa) Ltd for the processing of Uranium at Kayelekera thereby necessitating Paladin (Africa) Ltd to install it’s own massive diesel powered generators which require 1.5 million litres of diesel per month to drive the monthly production cycle. As a result of this arrangement; ESCOM is losing millions of kwacha every day due to inefficiency and inadequate capacity.

Furthermore, literature indicates Government of Malawi (2009) that ESCOM's problem of failure to meet demand has been compounded through electrification of rural and peri-urban areas under the Malawi Rural Electrification Programme (MAREP) which is carrying out grid extensions without taking into account the installation of new generation capacity. In addition, Malawi National Commission for UNESCO (2007) has observed that the crisis of power shortage is fuelled by increased urbanization and expansion of industrial and manufacturing sectors that has resulted into increased consumption.

Thus, the discussion in the preceding paragraph highlights the fact that Malawi has a major crisis in its electricity supply due to inadequate electricity generation to keep up with growing demand. This has ripple effects that are felt throughout the economy. Therefore recognizing the need to stimulate economic growth and development through provision of adequate energy, the Government of Malawi (GoM) has stepped up efforts to mitigate on insufficient generation and meet the electricity demand and reduce the impact on environmental degradation. However, the Financial Standard Foundation (2009) has suggested that the process of increasing the generation capacity is slow because the government has not been able to amass adequate funds needed to invest in new generation capacity and maintain existing infrastructure. Moreover, the government has been speeding rehabilitation works on the 64 MW Kapichira Hydroelctric Plant and also the government has plans to upgrade the Kapichira Hydroelectric power station to 128 MW by 2012, thus doubling the current capacity of the station.

In addition, ESCOM subscribed to the membership of Southern African Power Pool (SAPP) in order to mitigate on chronic shortage of power supply through electricity trade amongst SAPP member states. This point is further asserted by Girdis & Hoskote (2005) who has indicated that Malawi has joined forces with neighboring countries within the Southern African Power Pool (SAPP) block to have Malawi's grid system interconnected to Mozambique. However, it is also important to note that although ESCOM has been a long time member of Southern African Power Pool (SAPP), its transmission network is isolated from neighboring SAPP member countries. As result of this physical isolation, it is not able to trade electricity. The same author states that in 2004 Hidroelectica de Caborabassa (HCB) a joint venture between Portugal and Mozambique's Electricadade Mozambique was assigned to undertake the contractual obligation of supplying 300 MW of electricity to Malawi through Mozambique for a period of 20 years. Until today, nothing has so far taken place and there seems to be no indication that the power trade will be signed soon. Correspondingly, Malawi News (2010, January 17) observed that the government of Malawi through its Finance Minister expressed concern that power interconnection agreement signed in February 2007 with Mozambique; operationally puts Malawi at a disadvantage. For example, Malawi will be required to pay for the power interconnection service in foreign currency and the agreement will be risky if Malawi experiences shortage of foreign exchange. Therefore, the government of Malawi is meanwhile advocating for review of operational procedures. Moreover, it is important to note that the negotiations between Malawi and Mozambique on power trade have been slow.This raises a very big question as to whether Malawi will invest in the power interconnection to Mozambique to improve the power capacity and thereby meet the energy deficit and demand. The African Development Bank (2008), has argued that lack of commitment to the power trade arrangement grossly undermines one of the Malawi Government National Energy Policy objectives of improving the security and reliability of energy systems in Malawi. They also argue that although regional power integration plays a major role in greater access rates, reliability and stability of the power systems, there have been few success stories that have so far existed. The negotiations of power interconnections amongst countries have taken a very low profile due to burden of capital investment and political risk. For example, the African Development Bank (2008) specifically mentions the Republic of South Africa which produces 70% of electricity in Sub Saharan Africa has made little headway in its power trade with neighbours. It clearly states that only Lesotho and Botswana have benefited from its power trade arrangement. This illustrates the fact that power interconnection still remains a very big challenge within the Southern African Power Pool (SAPP) block and consequently power security will still be a recurring problem thereby affecting economic growth. For example, Malawi News (2010) reports that Malawi Economic Justice Network (MEJN) indicated that Malawi is losing approximately US$200 million a year because of under production that is associated with poor generation.

On one hand, anecdotal evidence leads to the fact that there is strong linkage between resource sector and growth of the economy. For example, the origins of rapid industrial and economic expansion in the United States in the years after 1879 were strongly linked to the exploitation of abundant non renewable energy sources such as energy and minerals. Indeed, in Malawi one of Malawi Energy Policy objectives is to maximize the economic benefit to the nation that can be realized from the exploitation of the nation's mineral resources. The government encourages investors to explore, delineate, evaluate and where viable exploit the resource using appropriate technologies. It is envisaged that one way to mitigate on shortage of energy is for the government of Malawi to be aggressive in the exploitation of non renewable energy sources such as coal or gas for provision of energy in order to supplement the deficiency of energy hence drive the resource based development. However, the exploitation of minerals such as coal or gas which would foster economic growth in Malawi has its own challenges. Some of the challenges include lack of geographical maps, specialized laboratory equipments for mineral exploration, shortage of geologists, among others.

Having looked at chronic shortage of energy in Malawi and mitigation plans by the government of Malawi, this section looks in brief at the reasons behind the chronic power shortage in SSA region. Various authors including Anderson & Opok (2008); Musuba & Naidoo (2009) & Nkweta & et al (2010) have echoed that the chronic power shortage prevalent in Sub Saharan African countries (including Malawi) has failed to meet demand for domestic and industrial use. The authors further say that the high demand for electricity is a result of high economic growth of more than 5% in Sub Saharan African region in recent years which has resulted in unprecedented growth in electricity consumption and demand. The same authors argue that the power shortage is attributed to the following reasons:

- Inadequate investment in generation and transmission infrastructure for over the last two decades.
- High power losses
- Deficient maintenance and low capacity utilization and availability factor.
- Hydraulic variations resulting from droughts

Additionally, the same authors lament that Sub Saharan Africa is increasingly becoming unable to meet electricity demand hence urgent measures are needed to address the inadequate generation capacity of electricity. Therefore indications from a number of studies above lead to the fact that Sub Saharan Africa has a glaring power deficit that manifests itself through extreme load shedding and sometimes total shutdown of generating plants.

Indeed, the evidence above has led to the conclusion that local energy is a potential solution and consequently the importance and urgency of investing in development of localized renewable energy technologies for rural poor communities cannot be overemphasized. In addition, various authors including Duke & et al (2002); Macias & Ponce (2006) & Obeng & Hans-Dieter (2009) have suggested that provision of reliable energy has been acknowledged as one of the vital organs for attainment of poverty eradication, especially within the framework of Millennium Development Goals. Moreover, the authors have argued strongly that lack of access to electricity is energy poverty that deprives the rural population advancement in their economic development. It is this realization that has become a major driver towards harnessing energy from renewable sources. Also evidence in support of this approach can be found in NEPAD-OECD Africa Investment Initiative (2009) who argue that in recent years several efforts have been made to popularize Renewable Energy Technologies (RETs) such as solar PV system in order to supply energy to the rural people without access to an electric grid connection. Correspondingly, in Malawi the main drivers to switch to renewable energy are driven by inadequate energy capacity, climatic change, health and social benefits and the vast solar resource (Table 2.4). This research study will argue that if power crisis is to be resolved/minimized in Malawi, it will need resorting to renewable energy technologies such as solar PV systems. However, increased funding, better regulations and greater capacity within the public sector should be factors to consider as well.

Key Priority Area	**Long or Medium Term Goals**	**Expected Outcome**
Energy Generation and Supply	• To reduce the number and duration of blackouts, increase access to reliable, affordable electricity in rural areas and other targeted areas (such as social facilitates). • Improve coordination and balance between the needs for energy and the needs of other high growth sectors (such as tourism).	• Reliable and sustainable energy supply and increased access. • Increased access from the current 7% to 30% by 2020 • biomass-commercial energy mix target of 75% to 25% is set for 2015. • Power supply is connected to SAPP.
Integrated Rural Development	• To promote the growth and development of rural growth centres.	• Enhance re-distribution of wealth to all citizens. • Reduced negative consequences of rural-urban migration
Agriculture and Food Security	Increase agriculture productivity. • No food shortages even in times of disasters (e.g. drought and floods). • Increased exports of food staples. • Increase the contribution of agro-processing to economic growth, move up the value chain in key crops, and increase exportation of agro-processed products. • To open up the linkages to the sea.	• Increased value added to agricultural products by rural farmers and orient smallholder subsector to greater commercialization and international competitiveness. • Food is available in sufficient quantities and qualities and supplied through domestic • All Malawians have at all times physical and economic access to sufficient nutritious food required to lead a healthy and active life. • Increased contribution of agro-processing to GDP. An active inland network in local and international shipping that facilitates trade and tourism in a safe manner.

Table 2. 4: Main Drivers to Switch to Renewable Energy Source in Malawi. Source: State of Environment Report (2002); IMF (2007); MGDS (2007-2011); APINA (2008); Nangoma (2008) & Nkhonjera (2009

2.2.2 Renewable Energy in Malawi

Having established the need for renewable energy as a critical element of the power production portfolio, this section critically reviews the relevant renewable energy technologies in Malawi. According to Mingyuan (2005), renewable energy is defined as natural energy that does not have limited supply. It can be used again and again, and will never run out. On the other hand, renewable energy is an infinite source of energy that includes biomass, wind, solar, tidal, geothermal, wave and hydro. Non renewable energy is energy that is limited in supply. Alternatively, non-renewable energy is energy, taken from "finite resources that will eventually dwindle, becoming too expensive or too environmentally damaging. These resources often exist in a fixed amount, or are consumed much faster than nature can recreate them. Fossil fuels (such as coal, petroleum and natural gas) and nuclear power are examples. The Malawi National Energy Policy (2003) state that renewable energy in Malawi consists of Biomass that include firewood, charcoal, agricultural and industrial waste, solar energy comprising of photovoltaic and photo thermal, wind, geothermal and hydroelectric. Furthermore, it argues that the growing demand in energy has caused a great importance to be attached to the exploration of renewable sources of energy. Consequently, some of the potential renewable energy resources in Malawi are discussed below.

2.2.2.1 Biomass

Malawi is endowed with substantial biomass energy reserves. Available evidence United Nations Development Fund (2003) shows that forestry resources were estimated to be 9.4 billion hectares in the year 2000 that could provide significant biomass energy. For instance, it is estimated by the Government of Malawi (2009) that wood thinning and residues in Viphya Plantations in Mzimba District could generate 100 MW capacity of electricity. Biomass which is mainly firewood is the major form of energy that is fetched in the bush by rural people and bought by urban population for household cooking and heating. Studies show Malawi National Energy Policy (2003) that biomass energy sources account for 97% of production and has the following proportions: 52% of biomass is used in its primary form as firewood and 7% is residues. The remaining 41% is converted to charcoal in traditional earth moulds at estimated thermal efficiencies having a range of 12% to 14%. Since most of the population lives in the rural areas of Malawi, energy requirements are mostly met by wood fuel, resulting in deforestation. The

Financial Standard Foundation (2009) report estimated that for the year 2008, household firewood and charcoal consumption were 7.5 million tons per annum, exceeding sustainable supply by 3.7 million. It is further indicated that the additional use of charcoal and firewood results in the destruction of between 50,000 to 75,000 of natural forests annually. On the other hand, the Malawi Biomass Strategy Paper (2009) envisages that for the next 15 years the demand for cooking fuels will increase. For instance, commercial firewood demand is predicted to rise from 890,000 to 1.25 million tonnes per year while demand for charcoal will almost double from the current 305,000 to 606,000 tonnes per year. Similarly, a good number of authors including Girdis & Hoskote (2005); Chiotcha & Kayambazinthu (2009) & Openshaw (2010) have expressed concern that the substantial use of biomass is linked to deforestation, ecological problems and pollution of the environment. The same authors have observed that maintaining the country's current biomass energy use imposes serious environmental costs and necessitates the search for alternative energy generation.

Correspondingly, United Nations Development Fund (2003) indicate that Malawi has vast resources of bagasse energy generation from sugar waste products. The sugar corporation industry in Malawi generates electricity using residuals from sugar extraction (bagasse) and is used to drive thermal/ steam power plants. For instance, Dwangwa Sugar Corporation in Nkhotakota district of the central region and Sugar Corporation of Malawi (SUCOMA) in Chikwawa district of the southern region use sugar waste products to generate 7.0 MW and 11.5 MW respectively. Moreover, United Nations Development Fund (2003) has estimated that the total installed capacity using biomass at DWASCO and SUCOMA have the potential of generating 10MW and 28MW, respectively. It is argued that the increased generation capacity by the two companies would assist the government's plans of rural electrification. In support of this position, United Nations Development Fund (2003) highlights that approximately 280 smallholder farmers in Dwangwa (Nkhotakota District) and 310 smallholder farmers in Nchalo (Chikwawa District) supporting the sugar industry through the supply of sugarcane would benefit from the project investments.

2.2.2.2 Wind

Wind is another renewable energy resource that could be used to overcome the energy crises in Malawi. Various authors including Malawi National Energy Policy (2003) & United Nations

Development Fund (2003) have noted that there is substantial wind power potential in Malawi. Karekezi & Kithyoma (2003) have noted that the average wind speeds are between 2 m/s to 7 m/s. Also they have observed that the upper band of Malawi wind speeds compares reasonably well with South Africa that has been reported to be one of the countries in Sub Saharan Africa with the highest wind speeds of about 7.2 m/s to 9.2 m/s. The same authors have noted that there have been imported wind technologies in the country from as early as 1940s however their deployment rate has been low. Most of the imported designs have had limited success, even in areas which have good wind regimes, a factor attributed to poor design, lack of maintenance, scarcity of spares, operation and lack of maintenance skills. It is apparent that the key factors influencing the dissemination of wind generation are not technological, but are more focused on policy issues such as institutional development and on financing and economic considerations. Moreover, establishing suitable frameworks that are intended to encourage expansion in the wind sector has an important role to play in Malawi. Despite low deployment rate, literature shows United Nations Development Fund (2003) that Malawi wind power has been found to be economically viable for small irrigation needs in the agricultural sector and water pumping in government institutions such as remote schools and clinics.

2.2.2.3 Mini and Micro Hydropower

Dunn (2007) has observed that Malawi is blessed with immense mini hydro potential. Apart from the 4.5 MW Wovwe hydroelectric power stations that supplies electricity to the Northern part of Malawi with isolated grid, there are several potential sites for mini hydro power generation in Malawi. The Ruo River in the southern region of Malawi with a mean average annual flow rate of 15 m^3/s has a potential of generating between 25 MW to 45 MW of mini hydro plants of 5 MW each at Zoa falls. In addition Dunn (2007) highlights the fact that a field study on the sustainable hydropower development of the Mulanje Massif in Malawi shows that the catchment of Mulanje has a potential of 11 MW and would be able to supply electricity to 30% of the households in Mulanje. Correspondingly, the Malawi Energy Policy (2003) & United Nations Development Fund (2003) have observed that the economically and technically viable potential for mini and micro hydro sites in Malawi has a total generating potential of between 745 MW to 1670 MW.

2.2.2.4 Geothermal

According to Dulanya (2006) Malawi has substantial potential for geothermal energy. The author indicates that almost all geothermal sources of the country are of the convective type. Moreover, it is made clear that geothermal systems derive their heat from the high heat fluxes from crustal rocks due to conduction or magmatic bodies at deeper levels as a result of convection and these activities are associated with areas in the rift valleys. Thus, due to Malawi's geological setting within the rift valley, there is high potential in numerous places of the country with conductive systems. It is said that a number of hot springs with temperature range of 15 ^{0}C to as high as 93 ^{0}C exist in all three regions of the country. An equally significant aspect of geothermal energy is given by Karekezi & Kithyoma (2003) who have noted that geothermal energy can be extracted by drilling wells to harvest concentration of steam at high pressures and at depths shallow enough to be technically and economically justifiable. Thereafter, the steam pipes carry the steam which possesses adequate energy to drive turbines that in turn generate electricity. Moreover, geothermal power exploitation has a number of merits when compared to conventional energy sources. Some of the merits of geothermal power are insignificant emissions (true for modern systems that re-inject water back to earth's crust) and the need for less space required for geothermal power development. Also, Karekezi & Kithyoma (2003) state that geothermal power plants require approximately 11% of the total land used by coal fired plants and 12% to 30% of land occupied by other renewable technologies. For example, the authors have observed that Kenya's geothermal production contributes 5.5% of the total national electricity consumption.

2.2.2.5 Solar Resource

Substantial evidence shows Som (1979); United Nations Development Fund (2003) & Mnella (2007) that Malawi is endowed with abundant solar energy. The country is among the tropical countries located between latitudes $9^0$22' and $17^0$3'S and longitudes $33^0$40' and $35^0$55'E with good solar radiation throughout the year. Being in the solar belt, Malawi receives mean solar radiation of approximately 6 kWh/m^2/day on the horizontal surface and 3,000 hours of sunshine per year. During the hot and dry season an average of 7 kWh/m^2/day to 8 kWh/m^2/day is normal. Various authors including United Nations Development Fund (2006, p 117) & Nkhonjera (2009) have shown that the magnitude of solar radiation in Malawi is perceived to be adequate for the application of solar PV systems for the supply of basic electricity in the off-grid rural communities in order to improve their livelihoods.

Analyses have found that, in similar circumstances in Sahara Desert, Mukukatin & et al (1994) & Ketlogetswe & Mothudi (2008) have observed that the CILISS project which installed 1.2 MWp of solar PV improved the quality of life of the people through photovoltaic driven health facilities, agriculture and commerce in order to mitigate on poor living conditions that were prevalent. Furthermore, the authors argue that generation of conventional power by using extensive grid is uneconomical and not affordable to the rural communities.

2.3 Policy and Energy Regulation

The Department of Energy Affairs is the main institution behind energy policies in Malawi whose main objective is to fully satisfy public need for quality modern energy services by effectively governing and facilitating the development of the robust, sustainable and efficient private sector driven energy industry.

The government's energy policy known as the National Energy Policy (NEP), aims at improving the energy sector's contribution to realization of the country's Vision 2020 and Poverty Strategy. The policy was approved in January 2003. It sets out short and long term policy priorities and strategies for the management of the energy sector. High on the agenda of energy sector reforms is to improve technical and economic performance of energy supply industries, the enactment of legislation for improved energy sector governance and rural electrification initiatives. The NEP also aims to establish a more liberalized and private sector driven energy supply industry through Malawi Energy Regulatory Authority (MERA). Additionally, Government of Malawi (2009) shows that the government of Malawi through the power sector reform strategy which was approved in 2003 strongly allows private sector participation and competition as a driver of the overall National Energy Policy and putting a strong emphasis on strategies for energy supply industries.

However, the International Monetary Fund (2007); United Nations Development Funds (2008) & Government of Malawi (2009) argue that the participation of the private sector in energy production and supply has been almost non-existent although there has been an improved climate of doing business. Dunn (2007) & Government of Malawi (2009) notes that the unreliable and chronic shortage of power in Malawi should have given opportunity for investors in power or independent power producers to invest in power. In support of this position NEPAD-OECD Africa Investment Initiative (2009) who have acknowledged that private sector involvement in power sector has potential benefits because of a number of reasons: filling the funding gap for projects, provision of managerial expertise, creating a more competive environment and can assist in reducing operating costs where weak revenue flows exist. Similarly, Karekezi & Kithyoma (2003) point to the fact that Sub Saharan African countries should involve the private sector in energy production and supply. The authors specifically mention Kenya as one of the most successful countries in energy generation in Africa that has involved the public and private sector in geothermal energy generation since 1956. Approximately 57 MW of geothermal energy has been installed that contributes 5.5% of the national electricity consumption. Also, Obeng & Hans-Dieter (2009) observed that the Ghana National Electrification Scheme through governments and donor support increased its total installed electricity capacity by 85% within a period of 12 years beginning 1999. Malawi is no exception, the Infrastructure Support Project (ISU) observed that the price for solar PV systems reduced by 17.5% when the government removed import duty on solar products for certified companies to make an effort in the promotion of the use of the technology. This contributed to high participation of the public and private sector in supply of solar equipment and there was high penetration rate of solar products on the market. Moreover, various authors including United Nations Development Fund (2006, p11-12) & Nkhonjera (2009) have reported that the number of solar PV installations per month in Malawi increased significantly by 400% between the years 2002 and 2005.

Indeed, the National Energy Policy recognizes the potential role renewable energy technologies such as solar PV can play in meeting the country's energy demand and has set out the following objectives:

- Promotion and development of sustainable renewable energy technologies.
- Promotion of information dissemination on the use of renewable energy technologies.
- Increase the access to energy sources by the majority of the population in order to raise the level of productivity.
- Promotion of education, research and training in renewable energy technologies at various levels.

Therefore, United Nations Development Fund (2006) states that the Malawi National Energy policy is focused on moving energy use away from traditional biomass to modern sources of energy (renewables) that can stimulate economic activity and reduce poverty as one way of meeting the objectives above. For this reason, targets have been set to reduce biomass reliance from 93% in 2000 to 50% in 2020. Correspondingly, ADB (2008) & UNDF (2006, p25) specifically mentions that it has plans through the Other Renewable Energy Sources Reform Strategy (ORESRS) to increase the renewable energy base in the energy sector from 0.2% to 5.5% by 2010. Similarly, the Malawi Growth Development Strategy (MGDS) whose core objective is provision of sustainable economic growth and infrastructure focuses on the increase of energy generation and penetration of electricity into the areas that are not currently served by the national grid from the current 7% of the total population to 10% by 2010 and 30% by 2020. However, a contrary explanation is given by Mnella (2007) who argues that the role of renewable energy in Malawi is suppressed by reliance on hydroelectric power which has a clear investment strategy and defined targets unlike renewables. Despite the criticism, the popularity of the role of renewables is undiminished. Currently, the Department of Energy is implementing two major projects in a bid to increase electricity access rates and reduce deforestation through extension of grid and solar PV. The projects are Malawi Rural Electrification Programme (MAREP) whose objective is to extend the grid to rural growth centres. The project is funded by fuel levy and road administration fund, and is implemented by ESCOM. The other project is the National Renewable Energy Programme whose core objective is promotion of solar energy and is funded by United Nations Development Fund. However, besides these positive developments, the United Nations Development Fund (2006) argues that the Department of Energy faces many challenges to fulfill the goals set up in the National Energy Policy document. It highlights that the Department of Energy has been receiving inadequate funds to carry out its roles such as designing of energy programmes and coordination of implementation. This has resulted in the department's failure to undertake all its obligations. Also there has been high staff turnover at the Department of Energy due to lack of training opportunities. Moreover, the department lacks representation of staff at district and regional level consequently making planning and programming of rural electrification very difficult. On the other hand, ESCOM has been involved in rural electrification by donor driven projects between 1980 until to-date focusing to extend its grid to major centres and tobacco farms. However, studies show that there has been minimal extension of ESCOM's grid to rural areas. Evidence in support of this position can be found in MCC (2010) who highlight that ESCOM donor driven rural electrification projects have been erratic and failed conform to any coherent strategy. In actual fact, they argue that ESCOM has given up on rural electrification on the basis that ESCOM incurs heavy losses and the rural electrification project is non profitable**.** And currently, ESCOM has focused its expansion of grid coverage in high density urban and peri-urban areas. This raises a lot of doubt if rural electrification and the set targets in the policy document will be achieved in the near future.

In conclusion, it can be said that although the National Energy Policy was established seven years ago; it has been generally slow in implementing renewable energy projects. Funding has been inadequate to showcase the viability of renewable energy technologies in provision of country's energy needs. The Department of Energy which is the engine room for promotion of renewable energy technologies has been under-funded to effectively carry out its obligations. Also although the Malawi Growth and Development Strategy acknowledges the importance of renewable energy technologies to meet deficiency in energy, the renewable energy technologies are given less attention by government in terms of financial planning and implementation. Moreover, it has been observed that the government pays significant attention to meet its energy deficiency through increasing the hydropower capacity and SAPP power trades (Table 2.4). Finally, it is envisaged that it would be commendable to advocate and align the National Energy Policy to address the power crisis in Malawi and in addition increase the ability of the National Energy Policy document to attract external funding and private sector participation.

Since ESCOM is the sole supplier of electricity in Malawi and is involved in generation, transmission and distribution of electricity operations, the Malawi government should set a deliberate policy towards improving power service delivery by encouraging the private sector to be involved in electricity generation, transmission and distribution. Moreover, to improve on service delivery, the government should set a law that each interested private sector should have a single license for either power generation for sale, transmission network operation and distribution network for the supply of electricity. The aforementioned arrangement will ease operation pressure on ESCOM thereby improve the electricity supply delivery.

It is evident that investment requirements for energy sector is large and the government will not be able to solely finance the sector as has been the case in the past. Therefore, there will be need to attract external funding in the energy sector. Some of the needed attractions include: reviewing existing energy pricing, promoting energy conservation and efficiency measures in all sectors of the economy and maximizing the operating performance of existing energy infrastructure.

2.4 History of Barrier Removal to Renewable Energy in Malawi (BARREM)

This section reviews in brief the BARREM project in Malawi. It explores the establishment of BARREM and the project outcome. The author included this project because it is one of the major projects that carried out solar PV systems installations in a bid to promote the use of renewable energy in Malawi. The project made some significant assessments and recommendations of solar PV systems in Malawi.

The Global Environment Facility (GEF) provides grants and concessional funds to developing countries for projects related to six focal areas: biodiversity, climate change, international waters, land degradation, the ozone layer, and persistent organic pollutants. The World Bank, United Nations Environment Programme (UNEP) and United Nations Development Programme UNDP) are the core implementers. Global Environment Facility was established in October 1991 as a $1 billion pilot program in the World Bank to assist in the protection of the global environment and to promote environmental sustainable development.GEF funds are contributed by donor countries. Evidence shows Mulugetta & et al (2000) that in 2002, 32 donor countries pledged $3 billion to fund operations through 2006. Also at the Fourth GEF Assembly in 2006, an additional $3.13 billion was committed. Malawi is amongst many countries in Sub Saharan Africa that qualified for the GEF grant because of its initiative to combat world climatic change through the environmental policy. The UNDP- GEF funded project known as Barrier Removal to Renewable Energy in Malawi was approved for funding in 2002 to a tune of US$ 7.3 million comprising of GEF resources and planned co-funded public and private sector resources and was intended to run until 2006. The project had a number of aims, all of which were intended to catalyze the development of the Malawi solar market for households, public institutions, commercial and agro processing sectors through capacity building and institutional strengthening, creation of an enabling environment, financing for renewable energy systems, promotion of renewable energy technologies and creation/support of public awareness. Furthermore, the project focused on programmes of similar nature in other developing countries and in Malawi the major player in the project was BARREM operating under the Department of Energy Affairs and was responsible for procurement of project materials and equipment at national level and carrying out training programmes for installers and end users. The Malawi Bureau of Standards (MBS) prepared standards for installation and specification of solar photovoltaic components. Other stakeholders and organizations participated in the programme as implementers and financiers.

2.4.1 BARREM Project Outcome

Although BARREM's aim was to demonstrate the viability of investments in solar photovoltaic systems and encourage widespread replication thus bringing electricity to as many rural households as possible, there were a number of challenges that project met. Available evidence shows United Nations Development Fund (2006) that specifically the project's objective was to install 9,000 Off Grid solar PV systems by its completion date in 2006 in order to promote the use of solar PV systems. BARREM initiated and implemented a number of interventions. The United Nations Development Fund (2006) report that although BARREM had made some significant contribution to the growth of the solar PV market and capacity building in Malawi, a number of targets were not met. The report highlights that "there were reasonable options for sustainability of all the main project activities, although in some cases there were significant risks". It is estimated that 6,600 solar PV systems had been installed at the time of writing the evaluation report against a target of 9,000. However it seems nobody knows the exact number of solar PV systems installed over the project period. Furthermore, the report indicates that there was no coordination between different players involved in promotion and support of solar PV installation in the country including among Government Departments. For example, Ministries of education, health and water had some cases conducted installations using uncertified companies. This is also true with donors. This undermined the quality of installations. The report further indicates the ownership and management of Off-Grid projects presents a greater challenge in terms of sustainability. The United Nations Development Fund (2006) report further argues that there is need to focus on developing tools that would address the question of sustainability and ownership of solar PV systems. This should include ownership transfer mechanisms and taking into account the period of such transfers could take. It recommended a solar PV tool kit that could provide standard benefit/cost analysis of different technologies. Such analysis could assist in promoting the technologies. Also highlighted in the report is development of toolkit for maintenance plans and methodologies for quality control with complete benchmarks. In spite all the BARREM efforts, some commentators have said that the contribution of solar PV to the electricity supply still remains insignificant because the project basically promoted small solar PV systems used for lighting purposes. An attempt was made to use solar PV powered tobacco barns, however the technology was found to be more expensive than traditional methods and therefore uneconomical. Furthermore, the report indicates United Nations Development Fund (2006) that very little effort was made to promote solar PV for other commercial purposes such as irrigation farming.

Despite the shortfalls, the BARREM report highlights some successful experiences during the implementation of the BARREM project. It acknowledges that the demonstration of the solar PV project at Eswazini in Mzimba District is a good example of the importance of harnessing renewable energy. The report indicates that the solar PV system provided lighting to a Community Day Secondary School and Agricultural Offices. Furthermore, the report states that solar PV system brought to the community extended hours of studying for students and work at the agricultural centre. Also the community was charging their mobile phones without walking long distances as it used to be before the solar PV system was installed.

In summary, it can be said that although there has been successes and failures in the implementation of renewable energy technologies in Malawi, there is growing evidence that policy makers are keen to integrate renewable energy technology in policies to meet energy demand. Furthermore, it has been confirmed by Nkosi (2005) & United Nations Development Fund (2006) that the removal of import duty on solar products is a clear sign of government's approval of the renewable energy technologies in Malawi. However, the government has to consider increased funding for the Department of Energy in order to meet its obligations. And also the government should find means of stimulating the public and private sector to be more aggressive in investing in production and supply of energy.

2.5 Current Status and Applications of Solar Energy in Malawi

Various authors including Government of Malawi Energy Policy (2003) & United Nations Development Fund (2003) have shown that solar energy in Malawi remains far from being exploited due to poor structural, operational and institutional challenges. Despite the bottlenecks, available literature shows United Nations Development Fund (2003) that solar energy in Malawi has been in use for generations. Some efforts have been made to harness solar energy using modern technologies like solar electricity generation (photovoltaic systems) and solar thermal systems. Photovoltaic systems have mainly been used for telecommunications, medical refrigeration, lighting and water pumping. In the context of solar thermal, it has found its application in solar water heating, crop drying and direct cooking. Solar cooking has SCI (2006) been introduced recently by Solar Cooker International in the early 2006 but on a small scale**.** Presently, some institutions are carrying out research and design activities aimed at harnessing solar energy. For example, available evidence shows United Nations Development Fund (2006) that Mzuzu University is teaching renewable energy courses and is carrying out training and research on various renewable energy technologies. However, a number of commentators including Government of Malawi Energy Policy (2003, p38) & United Nations Development Fund (2006) have bemoaned the lack of a data base for renewable energy projects which can be used for analysis and planning. Therefore, it is the aim of this research study to demonstrate how data can be collected, analysed and put into public domain on solar energy use in rural communities by using a community based solar PV model. Therefore, some of the applications of solar energy in Malawi are discussed below.

2.5.1 Education

Available evidence shows Government of Malawi Energy Policy (2003) & United Nations Development Fund (2003) that solar PV systems providing electricity for lighting purposes are common in some parts of the country, especially in rural hospitals and schools. For example, statistics show that the pass rates for students at two Community Day Secondary Schools, Makanjira in Mangochi district and Chigodi in Mchinji district improved from 20% to as high as 80% when solar lighting was installed at the schools. Also, the authors state that at house hold level, apart from provision of lighting, solar energy drives low powered electrical appliances such as television sets and radio receivers.

2.5.2 Agriculture

Studies show Government of Malawi Energy Policy (2003) & United Nations Development Fund (2003) that there are more than 50 solar driven water pumps installed in remote parts of Malawi. They are installed mainly in health centres and schools for provision of safe water and sometimes irrigation. It is argued that the water pumps can draw water at 100 m deep and would supply approximately 10,000 litres of water per day

2.5.3 Health

Available evidence shows Government of Malawi Energy Policy (2003) & UNDP (2003) that solar energy is used to drive solar fridges that store vaccines and other medicines. It is argued that there are more than 50 solar refrigerators in use in the country of which 25 are used in the health sector. Most of these are used in government and mission hospitals. The same authors have also linked reliable lighting systems to improved health care.

2.5.4 Telecommunication

Studies show Government of Malawi Energy Policy (2003) & United Nations Development Fund (2003) that solar energy was used in telecommunication in the early 1970s. It is argued that the Post and Telecommunications Department installed powered the PRD single channel subscriber radio terminal equipment with solar PV system at Zoa estate in Thyolo District. Currently more sophisticated solar driven telecommunication has been installed and is in use. It is also said that solar energy in Malawi is used to operate wireless radio handsets in remote rural health centres which are far away from major roads and referral hospitals for effective communication when there is an emergency.

2.5.5 Heating

Government of Malawi Energy Policy (2003) & United Nations Development Fund (2003) makes it clear that with endowment of high solar radiation estimated between 25 MJ/m2/day to 28 MJ/m2/day, photo-thermal applications are quite obvious in Malawi. Photo-thermal applications are applied in schools, both rural and urban areas, to substitute geyser water heating by hydro electricity or firewood. With significant numbers of hospitals and schools in many parts of the country, there is high potential for photo-thermal applications in Malawi. Studies show that about 500 solar thermal installations have been deployed in various schools and hospitals in Malawi however it is estimated that half of the systems are not working due to poor maintenance skills and lack of maintenance. Despite the fact that there are solar thermal installations in Malawi, their uptake is low when compared to other African countries in the SSA. Thus, it appears that Malawi, as a nation in SSA, is lagging behind the rest of the countries in SSA in terms of renewable energy production. This does not, however, suggest that Malawi is not progressing. It is well known fact that the leading, more developed, SSA countries have policies and incentives in place which promote the construction and use of renewable energy. However, the lesser developed countries such as Malawi are lacking in this respect as a result of inadequate funding for RETs projects. Therefore, as much as the government wants to progress towards cleaner energy use through promotion of RETs such as solar thermal, it is limited with funding resources to deploy RETs. Also the lack of use is perhaps an indicator of the need for renewable energy promotion in Malawi. Moreover, to change an entire country's energy sources takes time because of lower economic activity as a result of renewable energies being unable to supply base load power needed to power energy and labour intensive sectors.

2.5.6 PV Application at Police/Immigration Road Blocks

In Malawi there are designated road blocks along the main tarmac roads and some immigration boarder posts that are located in remote places far from major cities. The grid electricity in such areas is not supplied to police/immigration offices and staff houses because it is taken as an expensive adventure by ESCOM. However, Police /Immigration department workers usually work for long periods and at night for security reasons. In order to mitigate on this problem, the government of Malawi has installed mobile stand alone solar PV units to supply power for lighting at police/ immigration road blocks so that they can perform their duties effectively.

It is clear from the indications above that while there is already contribution from solar energy, there are challenges to tackle to enable even significant contribution in future. Applications such as household energy and water pumping have achieved acceptance and are making significant improvements to the quality of life to the communities it serves. Despite solar finding its application in Malawi, the diffusion rates are very low. There is need to see wide application of solar energy to achieve full potential of social and economic growth of rural communities. In addition, there is need to build a database on solar energy technologies. Some commentators United Nations Development Fund (2006, p83-85) have echoed that lack of information on renewable energy technologies weakens the drive towards application of renewable energy technology deployment consequently the future of sustainable energy remains uncertain.

2.6 Rural Electrification Programmes in Malawi

It is important to note that the Government of Malawi has incorporated renewable energy development into its National Energy Policy and Energy Development Strategy as well as in its poverty alleviation approach. Moreover, in order to achieve the targets of the renewable energy development, the government of Malawi is rolling out renewable energy projects. Therefore, this section reviews some of the renewable energy projects the government of Malawi is currently rolling out in the rural areas of Malawi. It looks at how the projects roll out and their major challenges. Finally, the section concludes at echoing that solar PV is a probable solution to rural electrification in Malawi.

2.6.1 Programme for Basic Energy and Conservation (ProBEC)

ProBEC facilitated a technology shift to more efficient cooking stoves, researched ways of improving on the stove design and investigated the marketing possibilities of these energy efficient devices between 2002 and 2006 when the programme was phased out. Available evidence shows Government of Malawi Energy Policy (2003) that the programme aimed at significant use of abundant traditional biomass in line with Poverty Reduction Strategy. It promoted the efficient use of biomass through the promotion of improved end user devices. The hub of the programme was the rural and urban households, institutions (e.g. schools, hospitals etc.) and private sector. The commercial approach model was the key to sustainability of the programme. The people were trained to make clay stoves and were equipped with marketing skills. The clay stoves were sold by the producers. In rural households, skills in building clay stoves was passed onto local women's' groups. Besides favouring a commercial approach, ProBEC had put a lot of emphasis on ‘training the trainers' by teaching extension staff how to train stove producers, so as to enable them to start producing, marketing and selling stoves independently. In addition, the extension staffs carried out quality controls and follow-up visits. In order to mobilize community support for the introduction of the new technology, local leadership and community-based organizations were brought on board. Despite putting quality control checks, the problem of quality in terms of cracks and short lifespan of stoves was the major challenge. For example, evidence shows GTZ (2004) that at Matanya site the following shortfalls existed: the lack of clay decomposing and storage, unskilled stove construction and lacking proper firing (right temperature and speed). Besides the technical challenges, there was no willingness among the villagers to buy stoves, because everybody assumed to know how to build a stove and regarded stove production as something everybody could do. The value of a well-constructed and fired stove was not considered as well and this threatened the sustainability of the programme.

2.6.2 Renewable Energy Programme

The Renewable Energy Programme was established in 1998 and seeks to promote Renewable Energy Technologies. Some of the objectives of the Renewable Energy Programme are: (i) to promote the development and implementation of the National Sustainable Renewable Energy

Programme (NSREP) (ii) the development and issuance of the National Energy Policy and (iii) to create an enabling environment to pave the way for renewable energy industry in Malawi that is responsive to the needs of the target homes and institutions through the use of renewable energy. To date, the required renewable energy policy is incorporated in the National Energy Policy through the Renewable Energy Project with specific plans and targets that have to be met in the medium and long term. Despite the great overall impact towards the achievement of the desired outcome to increase the use of renewable energy in Malawi, United Nations Development Fund (2008) notes that the Renewable Energy programme have the following challenges that threaten the smooth roll out of the programme: (i) there have been considerable delays in submitting financial and progress reports and quarterly work plans which are required for advances of funds and other project administrative requirements by the Department of Energy (ii) the project experienced lack of understanding by implementing partners of results-based management and monitoring to keep focused on the programmatic approach of an RE program and (iii) follow-up actions on audit findings were not put into practice to improve project accountability and financial procedures.

2.6.3 Malawi Rural Electrification Programme (MAREP)

The Malawi Rural Electrification Programme (MAREP) is a World Bank funded project which started in 2004. MAREP is the program where government supplies electricity to trading centres in rural areas and every financial budget sees two trading centers in every district benefitting from the initiative. It seeks to improve the rate of household electrification through the extension of distribution lines and the expanded use of solar power generation systems. In August 2010, available evidence shows Lilongwe Times (2010) that the Ministry of Mines, Energy and Natural Resources had revealed that the Malawi Rural Electrification Program (MAREP) would roll out into phase six and preparation was at an advanced stage. Moreover, it was reported that the Ministry of Mines Energy and Natural Resources had identified two trading centres from all the 28 districts in Malawi that were to benefit from the project for the year 2010. By that time, transmission poles had been allocated to the selected 52 trading centres. MAREP secretariat had identified the trading centres in conjunction with district development committees and Electricity Supply of Malawi (ESCOM). However, the government had lamented that the MAREP programme roll out affects ESCOM because it results in the overloading of the ESCOM grid system due to an increase in electricity consumers without exploring ways of increasing the generation capacity to take up new installations. The above facts illustrate that MAREP roll out has a big challenge to balance the new installations with limited ESCOM capacity to avoid worsening blackouts and load shedding so that the programme should be sustainable.

In summary, the philosophy behind the projects above is to offer the rural communities an alternative choice of energy thus enabling them to switch to cleaner energy technologies. The ultimate result of such an intervention is to contribute to increase in energy generation, which is one of the core objectives of National Energy Policy. The government of Malawi also aims to guide and inform the rural communities on appropriate energy technologies that are environmental friendly and on the other hand aims at dissemination of some important energy policy issues to the local communities. The government of Malawi makes it crystal clear through the Energy Policy that rural electrification will be achieved through a number of options. For example, it specifically positions solar PV as first priority as a means of achieving rural electrification. It argues that solar PV is advantageous to grid electrification because it is in modular form and ideal for remotest rural communities where there is no grid power.

2.6.4 Approach to Rural Electrification

Before analyzing the elements that must be included in the sustainability of solar PV projects in Malawi, this research study will review some approaches to rural electrification that can serve as solutions to the rural energy problem in Malawi. The following sections lay out the available approaches to rural electrification, analyzes their advantages and disadvantages, and helps understand the different end-uses each technology can meet. The approach to rural electrification in Malawi is homogeneous to that in other developing countries in Sub Saharan African region. Various authors including Government of Malawi Energy Policy (2003) & SAPP (2003) have reported that the common approaches to rural electrification are by: extension of existing grids, establishment of mini-grids, off grid generation and stand alone PV and each is discussed in detail below:

2.6.4.1 Grid Extension

Grid extension is provision of electricity to the rural/peri-urban growth centres by means of tapping electricity from the main grid and probably is the most viable alternative in the long term in a larger electrification programme. For example, in Malawi studies show Government of Malawi Energy Policy (2003) that MAREP has been utilizing the grid option to extend its high voltage power distribution lines of up to 66 kV. The main target area for MAREP has been expanding the distribution network to rural growth centres and trading centres where beneficiaries include: public institutions (e.g. health centres, schools, police units, and immigration and customs border posts) and other related institutions for the common good. Available evidence reveals Fishbein (2003) that this option provides substantial wattage that can be utilized for social and economic development at a larger scale in the rural communities. The same authors report that in Brazil, case studies show that there was a change in the socio-economic outlook of community that received water, electricity and infrastructure, with productive uses including electrification induced irrigation, operation of cereal mills, using electric pump and forage grinder. Various authors including SAPP (2003)**;** Hogervorst (2005) & Invernizzi & et al (2007, p 15) have commented that for large rural areas, close to the main urban areas, the typical approach used by developing countries is to provide electricity by extension of the national or regional grid. Moreover, the same authors indicate that in spite of the advantages that Grid extension might have over other approaches of rural electrification, it has the following disadvantages: (i) it has high investment costs and in some cases rough terrain will make grid extension to demand substantial investment but with little returns to the supply utility since rural remote areas have low electricity demand due to low load density (ii) environmental impacts from building and sustaining the grid and (iii) people may illegally tap the grid and thereby cause poorer quality of the power and this can also be hazardous for people.

2.6.4.2 Mini-grids

Available evidence shows ESMAP (2000) that Mini-grids are isolated grids that connect several households or even villages. They provide centralized electricity generation at the local level using a village distribution network and, when fed with renewable or hybrid systems, increase access to electricity without undermining the fight against climate change. The resource used for generating electricity for the mini-grid will vary according to village profile, availability of renewable resources, and fuel transportation costs. In most cases, a diesel generator, a wind-diesel-hybrid, or a small hydropower plant will be the least cost option. Because the distribution system is similar, mini-grids may be ‘upgraded’ in the future through grid connection. In addition, Fishbein (2003) reports that Mini grids have the potential for powering a broad range of productive uses, including small industrial units (common ones are tools for carpentry, welding and auto repair), battery charging, small scale agricultural grinding, milling and drying and ice-making for fisheries. However, ESMAP (2000) has indicated that implementing sustainable hybrid mini-grids involves complex technical, financial and organizational issues which must address the end-users and their needs, capacity building and training, tariff and subsidy setting, and institutional strength.

2.6.4.3 Off-grid Electrification

These produce power independently of the supply authority grid and are mostly based on solar PV however wind and biomass technologies are also used. It is argued Government of Malawi Energy Policy (2003) that the option offers the least cost for typical rural households which are more than 300m away from the next mini-grid line. Furthermore, they are especially appropriate for remote, environmentally sensitive areas, such as national parks, cabins and remote homes. In rural areas, small stand alone solar arrays often power farm lighting, fence chargers and solar water pumps, which provide water for livestock. For example, the government of Malawi has recognized the importance of isolated off-grid option through the national energy policy to be applied to remote locations as mentioned above. Additionally, SAPP (2003) & Hogervorst (2005) reports that the role of off-grid systems is becoming increasing important despite there is wide spread constraints to their applications.

The literature from various authors above have shown that solar PV has recently become a predominant solution to address energy problems in remote rural areas but requires different approaches to satisfy the needs of the local community. PV panels are particularly good for independent systems for the production of electricity, like street lighting, community facilities, or solar home systems. This fact is further sustained by the work of Karekezi (2002) who highlight that the advantages of solar PV systems have proven to be reliable, durable, require low maintenance, and last up to 30 years. Moreover, larger PV panels can be used for electricity-micro grids, although the technology might still be too expensive. However, the author points to the fact that the only main problems with solar PV are the high capital cost (as well as installation cost), the need of a battery, which has to be replaced every four to five years thus increasing operating costs, and the fact that they cannot be produced locally and that spares are expensive.

2.6.5 Balance of Systems for Solar PV

Since the research study will look at the sustainability of solar PV systems in Malawi, it is of great importance to review the balance of systems that make up a solar PV system so that a better understanding is sought about the functionality of each part in the solar PV system. A complete small-scale, stand-alone PV system in Malawi will constitute of the following system components:

- A small PV panel
- A battery
- A charge controller
- DC/AC inverter
- Set of wiring to form a solar PV system suitable for a specific application

Consequently, the components of a small scale PV system are discussed in further detail below.

2.6.5.1 Photovoltaic Module

Solar Energy International (2007) reports that a photovoltaic (solar) module is an electrical device that converts light energy into electrical energy and forms the basic element of each photovoltaic system. It consists of many jointly connected solar cells. Solar cells are connected and placed between a tedlar plate on the bottom and a tempered glass on the top. A thin EVA foil is sandwiched between the solar cell and glass. Semiconductor bus bars interconnect the solar cell on the upper side of semiconductor material which makes the solar cells to look like metal mesh. The metal mesh is deliberately made thin to minimize incident photon beam disturbance. Mechanical strength on the module framing is provided by an aluminium frame but plastic and stainless frames are also used. For example, typical crystalline modules power ranges from very few watts and reaching up to 200 W/module. Some manufacturer's produce preassembled panels with several 100 Wp. Over its estimated life a photovoltaic module will produce much more electricity than used in production and a 100 W module will prevent the emission of over two tones of CO_2 . However, it is important to note that although the module has been considered as one of the components in the balance of systems for solar PV, a detailed explanation of different panel technologies are covered in section 2.7.3

2.6.5.2 Charge Controllers

Various authors including James & Dunlop (1997) & Solar Energy International (2007) have reported that a charge controller is a device that regulates the rate of flow of electricity. The regulation of electricity flow is from the generation source to the battery and the load. The controller keeps the battery fully charged without over-charging it. When the load is drawing power, the controller allows the charge to flow from the generation source into the battery, the load, or both. Charge controllers stop charging a battery when they exceed a set high voltage level, and re-enable charging when battery voltage drops back below that level. A series charge controller or series regulator disables further current flow into batteries when they are full. A shunt charge controller or shunt regulator diverts excess electricity to an auxiliary or "shunt" load, such as an electric water heater, when batteries are full. Many controllers will sense when the loads have taken too much energy from the batteries and will stop the flow until sufficient charge is restored to the batteries. The feature greatly extends the battery's life time. Pulse Width Modulation (PWM) and Maximum Power Point Tracker (MPPT) are some of the technologies that are in use today. These technologies adjust charging rates depending on the battery's level in order to allow charging closer to its maximum capacity. Charge controllers may also monitor battery temperature to prevent overheating. Some charge controller systems also display data; transmit data to remote displays, and data logging to track electric flow over time. The cost of controllers entirely depends upon the ampere capacity at which the renewable system will operate and the features the end users would like to monitor.

2.6.5.3 Battery

Available evidence shows James & Dunlop (1997) & Solar Energy International (2007) that a battery is made of many cells and a cell is an electrochemical unit consisting of positive and negative plates divided by separators, immersed in an electrolyte solution and enclosed in a case. The photovoltaic module has no capacity of storing the generated electrical energy. Therefore batteries are used to store electrical energy in photovoltaic systems. In other words electrical energy that was not used by the loads during the day is stored in batteries. Consequently, the stored energy can be used at night or during the day when the weather conditions are bad. The storage battery also plays a major role of supplying energy to electrical loads at stable voltage and currents. Storage batteries in photovoltaic systems are charged and discharged; therefore they are designed to meet stronger cycles of charge and deep discharge. Typical solar system batteries lifetime spans from 3 to 5 years, depending heavily on charging/discharging cycles, temperature and other parameters. The more often the battery is charged/discharged the shorter the lifetime. The most important battery parameter is battery capacity, which is measured in Ampere hour. Battery capacity depends on discharging current; the higher the discharging current the lower the capacity, and vice versa. Batteries can be charged in many different ways, for example with constant current, with constant voltage etc., which depends on the battery type used. The charging characteristics are recommended and prescribed by different standards. Solar battery prices are higher than the prices of classic car batteries, yet their advantages are longer lifetime and lower discharging rates. Consequently, the maintenance costs of photovoltaic systems are lower.

In addition, this section will review performance characteristics and operational requirements for solar PV batteries. Therefore, the information in this section is intended as a review of basic battery characteristics and terminology as is commonly used in the design and application of batteries in PV systems. It is envisage that the understanding of battery characteristics and terminology is important for system sustainability and will also assist solar PV system designers to have a good understanding of their design features.

2.6.5.3.1 Depth of Discharge (DoD)

The depth of discharge (DOD) of a battery is defined as the percentage of capacity that has been withdrawn from a battery compared to the total fully charged capacity. According to Dunlop (1997) the state of charge and the depth of discharge will always add up to 100%. However, the DOD can be seen from two angles namely: the maximum and average daily DOD. Maximum DOD refers to the maximum percentage of full-rated capacity that can be withdrawn from a battery. Thus, maximum DOD is the maximum discharge limit for a battery and this is entirely depends on the cut off voltage and discharge rate. Dunlop (1997) highlights that fact that in solar PV systems, the low voltage load disconnect (LVD) set point of the battery charge controller determines the allowable DOD limit at a given discharge rate. Besides, the allowable DOD is generally a seasonal deficit, resulting from low insolation, low temperatures and overloads.

While the average daily depth of discharge refers to the percentage of the full-rated capacity that is withdrawn from a battery and this depends on the average daily load profile. It has been confirmed by Dunlop (1997) that the average daily DOD is greater in the winter months as a result of prolonged night load operation periods. It is further said that for solar PV systems with a constant daily load, the average daily DOD is generally greater in the winter due to lower battery temperature and lower rated capacity.

In addition Dunlop (1997) indicates that a battery bank can be severely damaged by frequent over-discharges. Therefore, to protect it from being overused, the battery bank needs to be sized large enough so that only a portion of its total stored energy will be used each time. This requirement is determined by the depth of discharge (DOD). For example, a 40% DOD is equivalent to a battery only being discharged at 40% of its total capacity each day. The DOD can be set from 30% to 80%, depending on the age and quality of the battery. New and high quality and specially designed 'solar' batteries tolerate deep discharges while old or low quality or car batteries, which are not designed for deep discharge can sustain only shallow discharges. Moreover, it is good idea for the user to specify the DOD based on the battery's specific characteristics and age.

2.6.5.3.2 State of Charge (SOC)

The state of charge (SOC) is defined as the amount of energy in a battery, expressed as a percentage of the energy stored in a fully charged battery. Discharging a battery results in a decrease in state of charge, while charging results in an increase in state of charge. A battery that has had half of its capacity removed, or been has been discharged by 50 percent, is said to be at 50 percent state of charge. Figure 2.4 shows the seasonal variation in battery state of charge and depth of discharge.

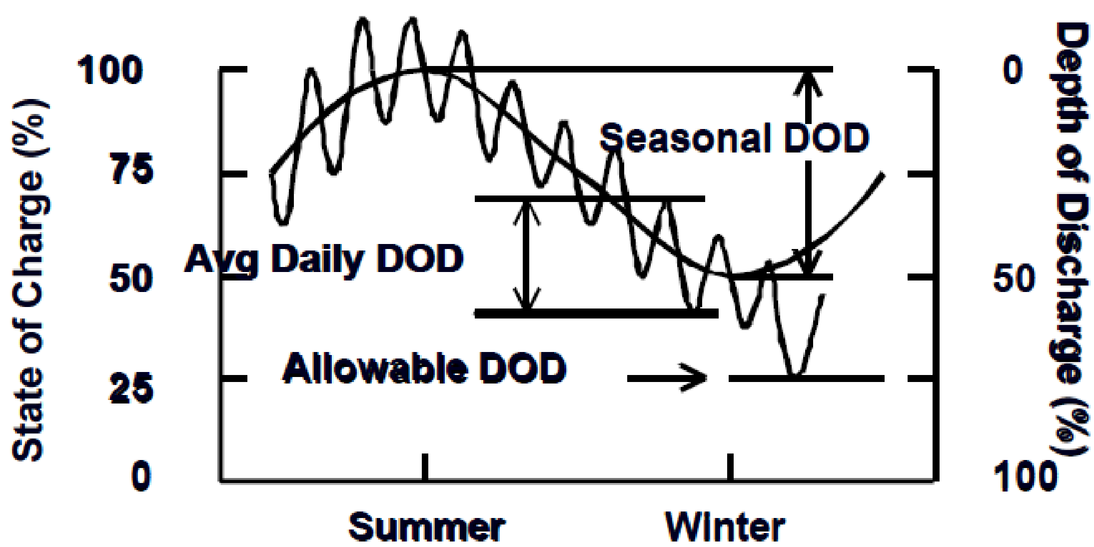

Figure 2. 4: State of Charge and Depth of Discharge: Source Dunlop (1997)

2.6.5.3.3 Battery Charge Efficiency

Available evidence shows Dunlop (1997) that battery charge efficiency is a function of battery state of charge. It is said that battery charge efficiency is high above 95% at low state of charge and the efficiency drops off near full charge. Moreover, it is argued that a determined charge against state of charge information is particularly important for solar PV systems where a large battery is used. That is to say, one designed to normally operate in the upper 10% or less of state of charge in order to achieve high load availability. Furthermore, it is indicated that if the size of battery is increased, it is gives more room for load availability and the battery will be operating at high state of charge. It has been confirmed Dunlop (1997) that if a 100 ampere hour battery has been used on a 30 ampere hour daily load, then the battery would be operating in the 70% to 100% state of charge regime on average. While if the same battery is operated at ten times the aforementioned daily load, then the battery would be operating at an average of 90% to 100% state of charge. Moreover, since charge efficiency decreases with increasing state of charge, the solar PV system with larger battery would require a larger PV array to account for higher losses associated with operating at a higher average state of charge. On one hand, since battery charge efficiency is a function of charge rate, then lower charge rates in large batteries would result higher charge efficiencies. Therefore, a decision on increased array size must be made with full knowledge of charge efficiency at the actual charge rate being employed.

2.6.5.3.4 Battery Maintenance

A battery is one of the solar PV system components that can easily be damaged if proper care has not been taken into account in the course of installation and operation. However, maintenance requirements differ and entirely depend on battery design and application. Some of the issues that must be considered in the maintenance of the battery include cleaning of cases, cables and terminals, tightening terminals, water additions, and performance checks. Performance checks may include temperature measurements, specific gravity recordings, conductance readings, cell voltage readings, or even a capacity test. Battery voltage and current readings during charging can aid in determining whether the battery charge controller is operating properly. Moreover, battery manufacturers often provide maintenance recommendations for the use of battery that must be adhered to in order to enhance the life span of the battery.

In summary, it can be said that all this lead to the fact that battery lifetime is dependent upon a number of design and operational factors such components and materials of battery construction, depth of discharge, state of charge, battery maintenance, charge rate etc. Therefore, as long as a battery is not overcharged, over discharged or operated at excessive temperatures, the lifetime of a battery is proportionate to its state of charge.

2.6.5.4 Inverter

Similarly, Solar Energy International (2007) has reported that an inverter converts the DC electricity from sources such as batteries, solar panels, or fuel cells to AC electricity. The electricity can be at any required voltage; in particular it can operate AC equipment designed for mains operation, or rectified to produce DC at any desired voltage. The alternating voltage from the output of an inverter can be rectangular, trapezoidal or sine shaped. Currently, the most expensive and good quality inverters are the ones that produce sine wave output. Inverter input voltage depends on inverter power, for small power of some 100 W the voltage is 12 or 24 V, and 48 V or even more for higher powers. Large inverters could be connected in parallel when higher powers are required. Inverters connecting a PV system and the public grid are purposefully designed, allowing energy transfers to and from the public grid. Inverters connected to module strings are used in wide power range applications allowing for more reliable operation. Module inverters are used in small photovoltaic systems. Such solutions are applicable to larger systems, however, in practice cheaper, and less reliable solution of central inverter or string inverters are used. Special design inverters are available for the purposes of hybrid systems. In most cases a powerful inverter includes charge regulator electronics, and not only the inverter. Modern inverters are the most sophisticated electronic devices implemented in photovoltaic systems. On top of high reliable electronics, which must be used, great care should also be taken on lightning protection. Inverters are based on microprocessor circuits, classic or RISC, and on power MOS or IGBT transistors.

2.7 Solar Photovoltaic Technology

This section is structured in two parts. Firstly, available knowledge with regard to history of solar photovoltaics and cell development is reviewed. The different panel technologies are examined and indicate that crystalline solar cell technology has advantage over other developed or other emerging solar cell technology because of their high conversion efficiencies as of now. Additionally, the chapter is important because it gives necessary background of the crystalline panel technology that is used in the Community Rural Electrification and Development Project (CRED) and on the same note available evidence shows United Nations Development Fund (2006) that the panel technology understudy is the same which is recommended by the government of Malawi for rural electrification. This review provides the wealth of information that is necessary to understand the principle of operation for different panel technologies. In the second part of this chapter, the photovoltaic module modeling techniques are reviewed. The idea is to acquaint the author of this research study how different authors argue in the assessment of the performance of photovoltaic module and look at parameters used for assessment of the performance of the module and it is not the aim of this dissertation to investigate such details as a great deal of specialists are already occupied in this pursuit. However, a basic understanding of the module performance assessment models is essential since it will assist to focus on the areas where information is less complete as regards to technical sustainability of solar PV systems in Malawi. Added importance of the review in this chapter will assist how this research study will propose to fill the gaps that do with lack of solar PV system performance data in Malawi.

2.7.1 History of Solar Photovoltaics

Photovoltaic is a duo word that means photos and light. The force that causes an electric current to move is known as electromotive force (e.m.f.) and is measured in volts. Consequently, Photovoltaic is the generation of electricity from light. According to Goetztberger & et al (2003) the photovoltaic effect was discovered by a French Physicist Edmond Becquerel in 1839 when he was experimenting on the wet cell battery. It was observed that there was an increase in the battery voltage when silver plates were brought in sunlight. In the year 1877 two Cambridge scientists, W.G. Adams and R.E. Day reported photovoltaic effect in solid substance known as selenium. However, Boyle & et al (2004) reports that there were variations of selenium properties when exposed to light. Moreover, Boyle & et al (2004) state that in 1883 Charles Edgar Frits constructed a selenium solar cell that is similar to the silicon solar cell which is in use today. It consisted of a thin wafer of selenium covered with a grid of very thin gold wires and a protective sheet of glass. But the cell was very inefficient; about 1% of the solar energy falling on the solar cell was converted to electricity. Additionally, the technology during that time had very little applications. Nevertheless, selenium cells eventually came into wide spread use in photographic exposure meters and later research work was devoted to the improvement of solar cell conversion efficiency as discussed in detail below.

2.7.2 Solar Cell Development

Various authors including Green (2001); Green (2003) & Wright (2003) report that history of solar cell production date back as early as 1940s when photovoltaic properties were demonstrated in PN junctions. In 1930 thermionic valves replaced silicon point diodes that rectified electrical signals at the junction by pressing a thin metal wire against polycrystalline silicon. However the most crucial factor in the development of solar cell has been the conversion efficiency.

According to Green (2001) & Wright (2003) the efficiency of solar cells at laboratory condition had increased from as low as a fraction of a percent to one percent in the early 1940s. The increase in the efficiency during that time was attributed to the use of growing pure silicon samples in controllable ways of forming the PN junction. Helium was implanted at high energy into the surfaces of P type polycrystalline silicon.

In addition, Green (2001); Wright (2003) & Goetztberger & et al (2003) observed that at a later stage in 1954, American scientists at Bell Laboratories produced the first solar cell through the process of diffusion by combining two techniques. One of the techniques was the Czochralski technique which is a method of crystal growth used to obtain single crystals of semiconductors (e.g. silicon, germanium, gallium and arsenide) and the other was by doping the PN junction with impurities at high temperature through the process of diffusion. A combination of these two techniques produced the first solar cells with an efficiency of 6% in 1956 and motivated interest in applications of photovoltaics for space vehicle power supplies. An increased use of the solar cell in the industry and extensive research efforts saw the improvement of the conversion efficiency to more than double (15%) by 1960. For example available records show that in 1958 the first solar cell powered satellite known as Vanguard I was launched by US space program. Studies show that the further research in improving solar cell efficiency was conducted by COMSAT Laboratories. It was argued that shallower diffusion combined with more closely metal spaced metal fingers could greatly improve the cell performance and make it more responsive to blue wavelength. Anisotropic chemical etches were used to form geometrical features on the silicon surface. The feature comprised of squared based pyramids. Terrestrial cell efficiency under sunlight of about 17% was demonstrated and reflection from the cell was greatly reduced. However available evidence shows that the terrestrial applications of the solar cell was not commercialized because the production cost was too expensive for the private sector to participate in marketing the product and governments had shown very little interest to support in subsidizing either research or production processes.

Also, Green (2001) & Wright (2003) report that in 1973 the OPEC oil embargo coupled with reductions in oil supply and escalating consumer prices on the market had driven a dramatic thinking by the international community that solar cells had a potential to be used in solar PV systems thereby minimize the dependence on oil imports. For instance, due to the effects of oil embargo, United States of America had increased funding on solar cell research from as low as $1 million to $400 million per year between 1973 and 1974. Also the Japanese government invested heavily in solar cell technology during that time. As a result of the aforementioned, research in solar cell improvement went on but the focus was mainly based on the ability of the cell to collect carriers generated by incoming photons and improvement of open circuit voltage. Another area that was the main focus in the improvement of solar cells in 1970s was screen printing of cell contacts and encapsulation. This led to development of laminated and encapsulated module that is still in use today.

2.7.3 Panel Technology

Solar cells can be produced in several different ways. Therefore, this section aims to provide a more detailed review of developed and emerging technologies that are applied to solar PV. Solar PV technologies that are found in common use today are reviewed and other emerging technologies that are promising but are not presently in use for solar PV are covered.

The basic element of photovoltaic technology is the solar cell. According to Goetztberger & et al (2003) & Turon (2003) a majority of solar cells have been manufactured from thin wafers cut from cylindrical mono crystalline ingots prepared by the exacting Czochralski (CZ) crystal growth method and doped to approximately one part per million with boron during ingot growth. Thereafter, a cell is produced from boron wafers by diffusion of phosphorous at high temperatures to form a P-N junction. The metal contacts to P and N type materials are attached to the solar cell by screen printing and the metal paste is heated at high temperature to drive off organic solvents and binders. The dimension of the solar cell formed is typically 10 cm by 15 cm in rectangular form or sometimes it can be in square form (10 cm by 10 cm). The cells are interconnected to form a module and a typical standard module will house 36 cells connected in series. The cell produces 0.6 V in great sunshine and with 36 cells; a total voltage exceeding 20 V is typical. This voltage is adequate enough to charge a 12 V lead acid battery. Also currents of the magnitudes of 2A to 5A are normal for this kind of cell in good conditions. The encapsulation comprises of a glass/polymer laminate with positive and negative leads from the series connected cells brought out in a junction box attached to the module rear. Literature shows that the module conversion cell efficiency lies between 12% to 16% ranges. However, this is reduced to 10% to 13% due to loss area as result of encapsulation and gaps between cells.

According Dobranski, Drygala, & Januszka (2009) solar cells can either be connected in series or parallel depending on the applications. The series connection aims at increasing the voltage while the parallel connection aims at increasing the current. Additionally, solar modules incorporate by pass diodes to avoid overheating of cells in case there are local hot spots due to partial shading of the modules. It is argued that overheating of the cells reduces the cell's efficiency. Currently, Sun Power and Sanyo Companies have reported conversion module energy efficiencies of 19.3% and 20.4% respectively.

Similarly, Kauko (2008) has reported that there are a majority of emerging companies that have produced modules at conversion efficiency around 14% to 17%. Also it is indicated that the emerging companies have gone at an advanced stage of generating increased power output and producing power on both sides of the module (front and back) however it is argued that most of the companies have not yet produced working modules from their design plans. Presently, literature shows Boyle & et al (2004) that as of August 2009, a world record efficiency level of 41.6% has been reached in the laboratory and most companies are improving the technology in terms of cost and efficiency. A number of approaches to reduce the cost of crystalline cells and modules or increasing their efficiencies have been under development for decades. These include cells using multi-crystalline rather than single crystal material; growing silicon in ribbon or sheet form; and the use of other crystalline PV materials such as gallium arsenide.

Various authors including Green (2001); Wright (2003); Dobrzanski & Drygala (2008) have indicated that crystalline silicone has become the most important material in the photovoltaics today and predictions make it clear that it will remain important and dominant for the next 30 years to come owing to its well balanced electrical, physical and chemical properties and established production technology. The same authors have observed that heavy reliance on crystalline silicon technologies trades efficiency costs. It said that crystalline silicon cells are derived from large wafers of purified silicon and the processes of purifying, crystallization and slicing silicon wafers have been the most expensive stages of solar cell manufacturing process. It is noted that the expense is derived from (1) cost of purchasing feedstock, (2) amount of material needed in the fabrication process and (3) capital costs of production equipment.

2.7.3.1 Monocrystalline Silicon Solar Cell

A Monocrystalline silicone cell (see Figure 2.5) is made from thin wafer of high silicon crystal, doped with minute quantity of boron Green (2001). Phosphorous is diffused into the active surface of the wafer. At the front of the electrical contact is made a metallic grid; at the back contact usually covers the whole surface. An antireflective coating is applied to the front surface. In addition, the mono crystalline silicon cell has a crystalline framework that is homogenous and its crystal lattice is continuous and unbroken with no grain boundaries. Large single crystals are exceedingly rare in nature and can also be difficult to produce in the laboratory. Single-crystal wafer cells tend to be expensive, and because they are cut from cylindrical ingots, do not completely cover a square solar cell module without a substantial waste of refined silicon. Consequently most Monocrystalline panels have uncovered gaps at the four corners of the cells. Most notably characteristic of the Monocrystalline silicone cell is that it has generally higher conversion efficiency compared to Multicrystalline silicone and Amorphous silicon. Available evidence shows Green (2001); Duke & et al (2002) & Willeke (2008) that the Monocrystalline silicone cell demonstrates high photovoltaic conversion efficiencies of around 15% to 18% (Table 2.5) and does not suffer from light induced degradation. The excellent performance of Monocrystalline solar is as a result of uniform structure that enables it to transfer electrons more efficiently. The emerging technology of Monocrystalline is that of silicon ribbon cells which are formed by cutting ribbons from thin Monocrystalline sheets and holds promise for the future due to reduced production costs.

In addition, literature shows Green (2001); Duke & et al (2002) & Willeke (2008) that Monocrystalline solar cells utilize less installation space. The reason being, they yield highest power outputs hence require the least amount of installation space compared to any other types of PV technologies. It is also confirmed that Monocrystalline solar panels produce up to four times the amount of electricity when compared to thin-film solar panels. Moreover, Monocrystalline solar cells have longest life span and many solar panel manufacturers put a 25-year warranty on their Monocrystalline solar panels. Besides, Monocrystalline solar cell tends to perform better than similarly rated Multicrystalline solar cells at low-light conditions. Despite the fact that Monocrystalline solar cells have the above merits, literature shows that

Monocrystalline solar cells the most expensive. Also, if the solar cell is partially covered with shade, dirt or snow, the entire circuit is open circuited. Another disadvantage of Monocrystalline solar cell is that the production process results in significant amount of waste coming from original silicon. This is so because the Czochralski process results in large cylindrical ingots to be produced (i.e. four sides are cut out of the ingots to produce silicon wafers). Furthermore, it has been noted Green (2001); Duke & et al (2002) & Willeke (2008) that Monocrystalline solar cells tend to be more efficient in warm weather however performance decreases as the temperatures rises and their efficiency decrease by 10% to 15%, so they are more consistent in output.

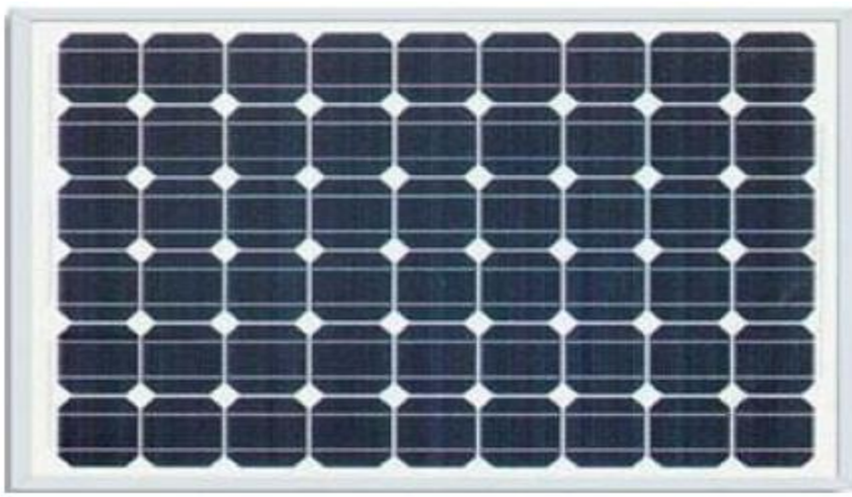

Figure 2. 5: Monocrystalline Solar Cell. Source: Green (2001)

Cell Material	**Thickness**	**Stage**	**Typical Module Efficiency**	**Maximum Record Module Efficiency**
Solar Junction 3		Emerging		44%
Microcrystalline Si solar cells	0.3 mm	Conventional	15% to 18 %	22.7%
Polycrystalline Si solar cells	0.3 mm	Conventional	14% to 15 %	15.3%
Amorphous silicon	0.00001 + 1 – 3 mm substrate	Intermediate	5% to 7 %	-
Cadmium Telluride	0.008 mm + 3 mm glass substrate	Emerging	6% to 9 %	10.5
Copper Indium Deselenide (CIS)	0.003 mm + 3 mm glass substrate	Emerging	7.5% to 9.5 %	12.1%

Table 2. 5: Current Conversion Efficiencies for Different Solar Cell Technology Source: Green (2001); Goetzberger et al (2007); Krishnan (2012) & Roberts (2013)

2.7.3.2 Multicrystalline Silicone Solar Cell

Multicrystalline silicone solar cells (see Figure 2.6) are made of silicon wafers that are made by wire sawing block cast silicon ingots into very thin slices or wafers of approximately 180 to 350 micrometer. Green (2001) has stated that Multicrystalline solar cells consist of smaller crystals or crystallites and are recognized by their visible grain known as metal flake effect. They also consist of antireflection coatings which increase the amount of light coupled into the solar. Silicon nitride is the most common antireflection coating that is used because it prevents carrier recombination at the surface of the solar cell. Available evidence shows Boyle (2004) that one single Multi Crystalline solar cell with an area of 12.5 cm^2 on a good sunny day is capable of generating a short circuit current of 0.3 A, an open circuit voltage of 0.5 V and maximum power of 0.12 W_p However, studies show Green (2001); Willeke (2008) & Dobrzanski & Drygala (2008) that Multi Crystalline Silicone solar cells are less efficient than Mono Crystalline Silicon cell because of low purity. It is said that the Multicrystalline solar cell has conversion efficiency of 14% to 15% (see Table 5). Multicrystalline silicone solar cells tend to be less efficient because Dobrzanski & Drygala (2008) light generated charge carriers (i.e. electrons and holes) can recombine at the boundaries between the grains within the Multicrystalline silicon. However, it has been found that by processing the material in such a way that the grains are relatively large in size, and oriented in a top to bottom direction to allow light to penetrate deeply into each grain, their efficiency can be substantially increased. Evidence in support of this position can be found in studies by various authors including Zhao (1995); Einhaus & et al (1999); Sopori (2002) & Green (2003) who argue that the introduction of hydrogen passivation steps by Silicon Nitride (Si_3N_4) layer deposition holds a tremendous promise for the improvement of the multi-crystalline solar cell efficiency to more than the current range. Also laboratory tests by the use of special lock in thermography technique on Multicrystalline silicone suggest Bauer & et al (2009) that it is prone to hot spots with avalanche. It is further argued that the hot spots are found to occur in regions of avalanche multiplication caused by acidic texture etch. The etch pits lead to strongly curved pn junction and resulting into reduced performance of the cell.

Thus, in summary, Multicrystalline solar cells have the following merits and demerits: Available evidence Green (2001) & Dobrzanski & Drygala (2008) shows that Multicrystalline solar panels production process is simple and costs less. This is so because the amount silicon waste is reduced in the production process. Moreover, Multicrystalline solar panels have low temperature tolerance therefore they perform poorly in high temperatures when compared to Monocrystalline solar cells. Also it has been noted Green (2001); Willeke (2008) & Dobrzanski & Drygala (2008) that the efficiency of Multicrystalline solar panels drop by 20% in elevated temperatures of 50^0 C. On one hand, it has been observed that heat affects the performance of solar panels and shorten their life spans. Therefore this type of panel is vulnerable to short life span because of its low tolerance to high temperatures. Another point worthy considering is that Multicrystalline solar cells need larger collection area to output the same electrical power you would with a Monocrystalline solar cell.

Figure 2. 6: Multicrystalline Solar Cell. Source: Green (2001)

2.7.3.3 Thin Film Solar Cell

Available evidence shows Harmon (2000) that the thin film panel technology (see Figure 2.7) has emerged on the solar market owing to the need of the research group to increase the photovoltaic conversion efficiency and the high cost of crystalline silicon due to high demand. These include amorphous silicon (a-Si), Cadmium Tellride (CdTe), Copper Indium Diselenide (CIS) and Copper Indium Gallium Selenide (CIGS). Thin film cells are made of ultra-thin (10^{-6} metres) semiconductor which is applied to thin inexpensive steel backing. The backing can be made from glass, flexible metallic foil, high temperature polymers, or sheets of stainless steel. Thin film use 1/20 to 1/100 of the material needed for crystalline silicon semiconductors. Consequently, they require much less energy to fabricate than traditional crystalline silicone solar cells and can be produced in a number of techniques. Additionally, lower volumes of production material for thin film PV panel technology, as compared with crystalline silicon, result in lower material cost and make it significantly more affordable than Multicrystalline silicone cells. In other words, thin film solar cell technology exhibit mass manufacturing cost reduction as compared with crystalline silicone. Moreover, thin film solar cells find their way in many potential applications because they can be made flexible and appealing. Despite thin film panel technology having an upper hand in terms of production cost and flexibility, Green (2003) reports that they have not commercially attained field efficiency greater than 13% as compared with 15% to 18% efficiency of Monocrystalline and 14% to 15% Multicrystalline silicone solar cells. In addition, thin film solar cell technology tends to degrade faster than crystalline solar cell technology hence has a shorter warranty. Besides, thin film panel technology is not applicable for most residential installations. Furthermore, it has been confirmed Harmon (2000) & Green (2003) that thin film solar cell technology requires a lot of space. Also, it has been noted that Monocrystalline solar cells produce four times amount of electricity as thin film solar cells for the same amount of space. Besides, because of poor space efficiency, there are increased costs for cables, support strictures and solar PV accessory equipment.

Figure 2. 7: Thin Film Solar Cell. Source: Green (2001)

2.7.3.4 Nanocrystal Solar Cell

According to Boyle & et al (2004) this group of photovoltaic solar cells is based on nanotechnology that aims to manipulate molecules and atoms at extremely small scales, measured in billionths of a metre or nanometers. These tiny particles and structures are known as nanoparticles or nanostructures; crystals of such sizes are called nanocrystals. Nanoparticles consisting of extremely small collections of atoms of semiconducting material are called quantum dots. In addition to advances made to old types of PV cells, research has been made in the creation of new types of cells. Moreover, Boyle & et al (2004) has indicated that one of the most promising of these new photovoltaic technologies that has received considerable attention over the past decade is the quantum dot photovoltaic cells based on dye sensitized titanium dioxide (TiO2) semiconductor. They are fabricated from the spin coating process. The quantum dot solution is placed on a substrate which is then rotated at reasonable high speed. The solution spreads out uniformly and the substrate is spun until the required thickness is obtained. The cells are surrounded by a carbon layer bounded by glass on either side. Moreover, Boyle & et al (2004) states that the mesoscopic texture of the titanium dioxide film in these cells provides a large cross-sectional area of light harvesting by surface anchored charge sensitizers while at the same time maintaining an excellent contact with electrolytes. It is noted Kong et al (2007) that the efficient generation of electricity is due to ultra fast injection from a photoexcited dye into the conduction band of an oxide semiconductor and the subsequent dye regeneration and hole transportation to the counter electrode (Figure 2.8). It is envisaged that this kind of photovoltaic cell will provide an economically credible alternative to the conventional inorganic photovoltaic devices owing to their high efficiency conversion efficiency and low production cost.

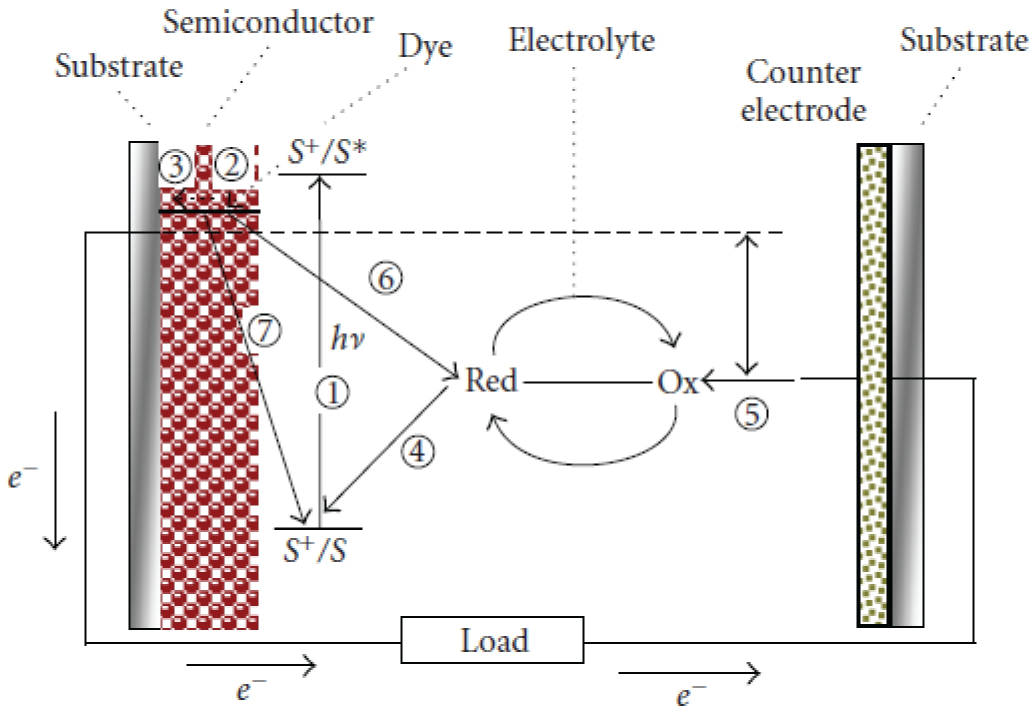

Figure 2. 8: Nano crystalline solar cell. Source: Kong et al (2007)

2.7.3.5 Solar Junction 3 Solar Cell (SJ3)

Available evidence from National Renewable Energy Laboratory has shown that Solar Junction 3 Solar Cells (Figure 2.9) has achieved 44% efficiency under concentrated sunlight of 947 numbers of suns (referred to as Suns). It is said that the SJ3 solar cell utilizes three layers of materials in the cells and these materials create multiple junctions with each having different band gap energies. Band gaps are energies that characterize how a semiconductor material absorbs photons, as well as how efficiently a solar cell made from that material can extract the useful energy from those photons.

Thus, it has be confirmed Krishnan (2012) & Roberts (2013) that the arrangement of the three layered materials in the SJ 3 solar cell has enhanced the absorption of maximum number of photons in the cell. It is said that by using multiple layers of materials in the cells, multiple junctions are created each with different band gap energies. Therefore, each layer converts a different energy range of the solar spectrum. In addition, it has been highlighted that the SJ3 solar cell has removed the weakness of single photovoltaic junction cell which suffer from energy loss.

On one hand, it has been noted Krishnan (2012) & Roberts (2013) that the low efficiencies recorded in conventional solar cells with single junction is that their construction is characterized by single band gap energy which leads to absorption of photons that very nearly match the band gap of the semiconductors in the cell. In this case, higher energy photons lose their excess energy as heat and low energy photons are completely rejected leading to complete energy loss.

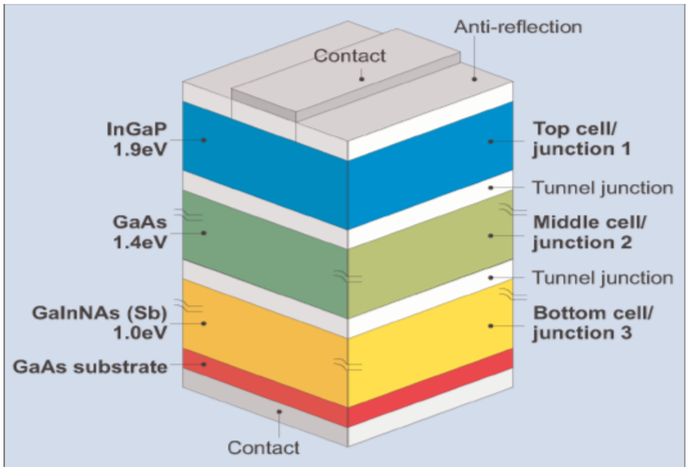

Figure 2. 9: SJ3 Solar Cells. Source: Cooke (2013)

Furthermore, it has been indicated Krishnan (2012) & Roberts (2013) that the SJ3 solar cell has the following advantages;

- It has replaced the standard cell now used by the space and concentrated photovoltaic (CPV) industries and is seen to have increased the space and CPV power output by close to 10%.
- By using dilute nitrite junction, the weight of the cell has been reduced significantly due to that fact that the germanium layer which constitutes about 90% of the weight of the cell has been eliminated.
- The significant reduction in weight has resulted in reduction in cost. It is said that the SJ3 cells use inexpensive lenses which have the capability of collecting the light and beaming it directly at each cell. As a result of this, the SJ3 cell has been confirmed to provide low cost electricity in locations where there are clear skies and good irradiation.

2.7.4 Photovoltaics Module Modelling Technique

Available evidence shows Kauko (2008) that the performance of solar cell which is the paramount building block of solar PV module is characterized by four general parameters which are derived from the current – voltage characteristic (Figure 2.5) measured under standard test condition (STC) which constitute Air Mass 1.5 spectrum, 1 kWh/m^2 and 25 ^{0}C ambient temperature. The four general parameters are short circuit current, open circuit voltage; fill factor and energy conversion efficiency. However, normal operating conditions of solar PV systems are rarely at STC. Correspondingly, Carr (2005) has observed that the performance is dependent on geographical location, season and meteorological conditions. It is indicated that under maximum sun conditions, the module temperature can be more than 25 ^{0}C and reaching approximately 80 ^{0}C. This lowers the efficiency of the module, as the fill factor and open circuit voltage are temperature dependent parameters. However, in order to understand the efficiency of solar cell, a basic understanding of the theory and four common parameters is essential, in as much as they relate to photovoltaic solar cell efficiency. These are discussed and presented below.

2.7.4.1 Theory of I -V Characterization Curve

The circuit shown in Figure 2.10 shows the equivalent circuit of solar PV cell. By using source transposition theorem, the circuit can be modelled as a current source in parallel with a diode. The principle of operation of a solar cell depends on light falling on it. Therefore, in darkness the solar cell is not an active device, it behaves like a diode. In addition, when the intensity of light increases, current is generated by the PV cell as depicted in Figure 2.10

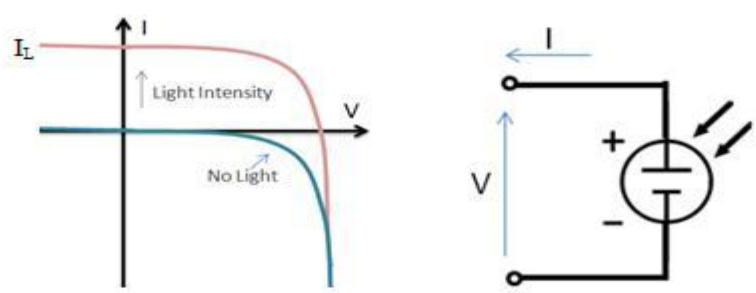

Figure 2. 10: The I-V Curve of a PV cell and Associated Electrical Circuit. Source: Kauko (2008) & Wu et al (2004)

From the equivalent circuit in Figure 2.9, the sum of output current I and diode current I_D is equal to the photon generated current I_ℓ. Mathematically it can be represented by

$$I + I_D = I_\ell \quad (1)$$

$$\text{Hence } I = I_\ell - I_D \quad (2)$$

By substituting I_D using the Shockley's equation, we have

$$I = I_\ell - I_D = I_\ell - I_o\left(e^{\frac{qV}{kT}} - 1\right). \quad (3)$$

Source: Longatt (2005) & Kauko (2008)

Where I_0 is the reverse saturation current of the diode, I is the output current, I_ℓ is the photo generated current, q is the electron charge (1.6 x 10^{-19} C), k is the Boltzmann's constant (1.38 x 10^{-23} J/K), T is the junction temperature in Kelvin (K), R_{SH} is the shunt resistance, R_S is the series resistances and V is the voltage across the diode Wu et al (2004). However, experiments have shown that a five parameter model that involves two diodes can also be used and improves the accuracy of the circuit. Therefore, by connecting the shunt (R_{SH}) and series (R_S) resistances to the circuit in Figure 2.9, we obtain an equivalent circuit as shown in Figure 2.11 and equation (3), where n is the ideality factor (typical range of values between 1 and 2).

$$I = I_l - I_0\left(exp^{\frac{q(V+I\cdot R_S)}{n\cdot k\cdot T}} - 1\right) - \frac{V + I\cdot R_S}{R_{SH}} \quad (4)$$

Source: Longatt (2005)

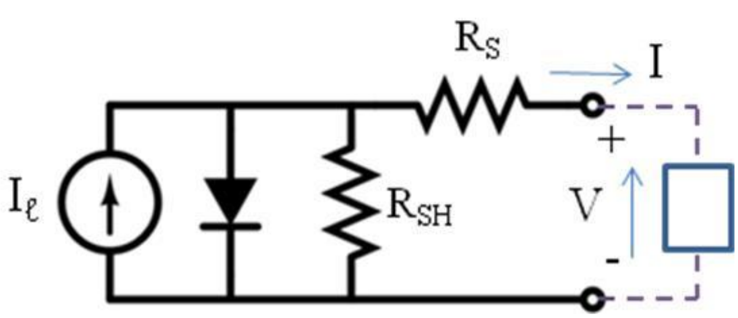

Figure 2. 11: Simplified Equivalent Circuit Model for a Photovoltaic Cell. Source: Wu et al (2004) & Carr (2005)

Figure 2.12 represents the Current against Voltage characteristic of an illuminated photocell. If a load is connected across the output terminals of an equivalent circuit of a photodiode and assuming that the load voltage is increased from zero to open circuit voltage (about 21 V), a number of performance parameters for cell can be determined from this data as described in the sections below:

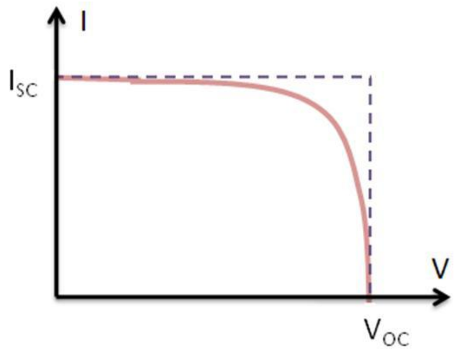

Figure 2. 12: Illuminated I-V Curve Sweep. Source: Wu et al (2004)

2.7.4.2 Short Circuit Current (I_{sc})

As seen from Figure 2.12 the short circuit (I_{sc}) current is the greatest value generated by a cell. It is produced by short circuit conditions when the voltage is 0. This is a point when the circuit impedance is minimum. I_{sc} occurs at the beginning of the forward bias sweep and is the maximum current value in the power quadrant. For ideal diode, this maximum current value is the total current produced in the solar cell by photon excitation.

$I_{sc}=I_{max}= I_\ell$ for forward-bias power quadrant

2.7.4.3 Open Circuit Voltage (V_{oc})

The open circuit voltage (V_{oc}) occurs when there is no current passing through the cell.

V (at I=0) = V_{oc}

V_{oc} is also the maximum voltage difference across the cell for a forward-bias sweep in the power quadrant.

$V_{oc}= V_{max}$ for forward bias power quadrant. The open circuit voltage can also be expressed as

$$V_{OC} = \frac{nkT}{q} \ln\left(\frac{I_L}{I_0}\right) = V_t \ln\left(\frac{I_L}{I_0}\right) \qquad (5)$$

Source: Longatt (2005)

Where V_t is thermal voltage and is given by

$$V_t = \frac{mkT_c}{e} \qquad (6)$$

Where e is the electron charge (1.6 x 10^{-19}C), T_c is the cell reference operating temperature, k is the Boltzmann's constant (1.38 x 10^{-23} J/K) and m is the dimensionless diode curve fitting factor

From Fig 2.11, it can be seen that the cell is a current source and R_s represents the structural resistances of photovoltaic panel, therefore in any real case the series resistance R_s will result in some power loss thereby decrease the overall power generated by the cell. Anecdotal evidence suggests that the series resistances occur at high values of currents and these can only be possible when the irradiance is high (i.e. on a good sunny day). Also the shunt resistance is inversely related with shunt leakage current to the ground. Therefore, in general, it can be said that the solar PV efficiency is insensitive to variation in shunt resistance hence the shunt leakage resistance can be assumed to approach infinity without leakage current to ground. On the other hand, this means that a small variation in series resistance will significantly affect the solar PV output power.

Finally, it can be seen from equations (3) to (6) that most important parameters that dictate the performance of solar PV cell are the cell temperature and the solar irradiance. Indeed, the correct analysis of their behavior is crucial to correctly predict the performance of the PV cells and arrays.

2.7.4.4 Maximum Power (P_{MAX}), Current at P_{MAX} (I_{MP}), Voltage at P_{MAX} (V_{MP})

In electric circuits, power is calculated from the product of voltage and current (P= IV). From Figure 2.13, it can be seen that when the short circuit current (I_{sc}) is a maximum, the open voltage is zero. If we plot the Power against Open Circuit Voltage characteristic on the same axis with the Current against Open Voltage characteristic, the maximum power can be obtained from the curves at a point (V_{MP}, I_{MP}).

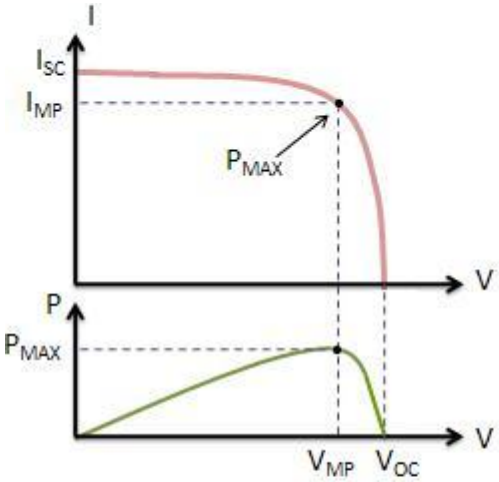

Figure 2. 13: Maximum Power for an I-V Sweep. Source: Longatt (2005) & Kauko (2008)

2.7.4.5 Fill Factor (FF)

Fill Factor is the ratio of maximum power that can be delivered to the load and the product of short circuit current (I_{sc}) and open circuit voltage (V_{oc}). Alternatively, FF can be defined graphically as the ratio of the rectangular areas depicted in Figure 2.14 and is often expressed as a percentage. Experiments have shown that a larger fill factor is desirable because it corresponds to an I-V sweep that is more like a square-like. Typical Fill Factors range from 0.5 to 0.82.

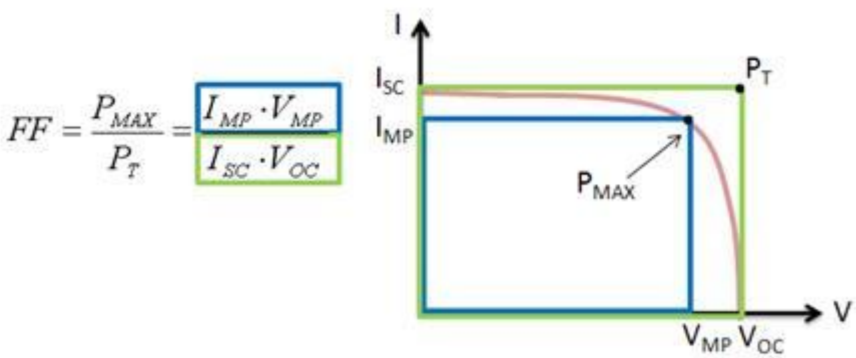

Figure 2. 14: Calculation of Fill Factor from the I-V Curve Sweep. Source: Longatt (2005)

2.7.4.6 Efficiency (η)

Efficiency is the ratio of maximum power P_{MAX} to the incident light power P_{in}. Therefore, the equation of efficiency is given by:

$$\eta = \frac{P_{\max}}{P_{in}} = \frac{I_{\max} V_{\max}}{AG_a} \qquad (7)$$

Source: Longatt (2005)

Where G_a is the ambient irradiation and A is the cell area

P_{in} is taken as the product of the irradiance of the incident light, measured in W/m^2 or suns ($1000\ W/m^2$), with solar cell (m^2).

A detailed literature review in the area of solar PV systems performance modelling has been done through the duration of this research. The objective was to gain an in depth understanding of models which have been applied to assess solar PV systems performance. Literature review shows Hermann & Wiesner (2000) that solar PV systems performance can be analysed by both simulation and analytical methods. Some authors argue Tiwari & Sodha (2006) that long term performance of solar PV systems is essential since it evaluates the quality of the system during the time of its useful life. One of the most important features of the useful life of the solar PV system is the energy payback time which lies within the range of 10 to 15 years depending on the performance and insolation of the PV module. Energy payback time takes into account the length of deployment required for a solar PV system to generate an amount of energy equal to the total energy that went into production. According to U.S Department of Energy (2011), EPBT is dependent on three major factors: (i) the conversion efficiency of the photovoltaic system (ii) the amount of insolation that the PV system receives and (iii) the manufacturing technology that was used to produce the photovoltaic cells. Therefore, an increase in conversion efficiency results in an increase in the performance of solar PV system consequently the energy payback time can be reduced. Also quality of the system must aim at daily energy supply and long operational periods. It is further argued that energy supplied to the end users depends on the initial design, sizing and component ageing that influence and reduce the availability of power to the consumers. Also technical failures reduce the actual operating time of the system. Therefore, fundamentally various authors including Hermann & Wiesner (2000); Diaz & et al (2006); Topic & et al (2007); Kumaravel & al (2007) & Skocozek & et al (2009) agree that solar PV module parametrically depends on meteorological, design and operating parameters such as ambient temperature, wind speed, irradiation intensity, module temperature, module area, maximum power point current and voltage, open circuit voltage and short circuit current. And these can be analysed to obtain or improve the solar PV system conversion efficiency. Additionally, it is envisage that rural electrification in most developing countries is achieved through off grid systems consequently assessment of off grid systems such as solar Photovoltaic is crucial to system sustainability.

A large body of theoretical as well as experimental studies on solar PV system performance has been carried out for some decades until now. Diaz & et al (2006) presented a deterministic model of evaluating availability of energy on demand side. The authors argue that dependability is a theory that takes into account several factors such as:

- Failure modes identification and valuation
- Risk and accidental analysis
- Maintenance planning
- Energy interruption
- Cost estimation of energy shortage
- Quality improvements for future practices

It is indicated that in off grid systems, studies are mainly focused on energy balance estimations with ideal components by means of Loss of Load Probability (LLP) or the size of system parameters that are utilized for energy balance. In their model it is assumed that in off grid power systems, interruption to the loads can be caused by technical failure and in adequate storage of energy. Additionally, it is argued that technical failure must be studied in relation to the time when the system is being serviced or repaired since the actual parameter to evaluate the system characteristic is the availability of energy on demand. On the other hand the energy storage components should also be studied since components change their nominal values during operation consequently decreasing the energy supply. The model of dependability is shown in Figure 2.15 below:

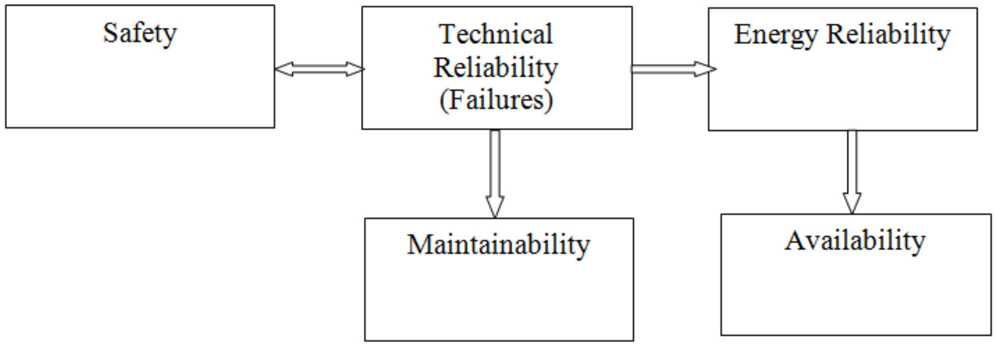

Figure 2. 15: Dependability Model. Source: Diaz & et al (2006)

Longatt (2005) proposed and validated experimentally a simple model to predict the performance of solar PV system. The circuit based simulation was used to determine the cell characteristics with changes in meteorological conditions such as temperature and irradiance. The solar PV module model was based on the Shockley diode equation and the general model was implemented on Matlab version script file that accepted meteorological conditions as system variable parameters and output the I-V characteristic curve. It is argued that the Solarex MSX60 PV module was chosen for modelling because of suitability for off grid applications. The PV module had a nominal maximum power rating of 60 watts and 36 polycrystalline silicon cells connected in series. Analytical expressions for the operating parameters of a solar PV system module such as short circuit current, open circuit voltage, fill factor and maximum power output were obtained and used in circuit simulation. In general the model analyzed the effect of temperature and insolation on solar PV system performance.

Radiemska & Klugmann (2006) presented by a model of increasing the output power of a solar PV module by tracking the Maximum Power Point (MPP). The model has been based on a heat sink in order to stabilize the temperature of a PV cell during illumination. A mono crystalline solar cell has been used to determine the MPP and results indicate that the conversion efficiency of Mono crystalline silicone solar cell decreased from 13.1% at a temperature of 25^0C to 10.1% at a temperature of 60^0C. They attributed the power losses at MPP are due to the following factors:

(1) Influence of temperature and illumination profiles on MPP

(2) Low radiation and shadowing effects

(3) Tracking losses of the MPPT unit

(4) Connection losses of the system components

(5) Conversion losses (dc/dc and dc/ac)

Atlas & Saraf (2007) proposed a photovoltaic array simulation model for Matlab-Simulink GUI Environment that can be used as part of the distributed power generation systems. It is argued that since solar PV power fluctuates with changes in illumination and temperature of the cell time, there is need to perform simulation for system analysis and parameter settings. Results show that the proposed model can be interfaced to AC loads and be part of distributed power generation system however the model lacks control mechanism to track the maximum power point which is of significant importance to off grid systems.

Various authors including Topic & et al (2006) & Topic & et al (2007) proposed a model to evaluate the outdoor performance of solar PV system by the technique of energy rating. The model has been based on analysis of energy rating of solar PV modules over a year. It is argued that accurate predictions of the conversion efficiency of solar PV modules require analysis of the annual average of time-dependent irradiance, temperature and solar tilt angle distributions at the installation site. Additionally, it is made clear that the effective efficiency can be calculated as a ratio of total available energy generated in a year divided by the annual solar energy. However, they reported that conversion efficiencies of most solar modules vary by a margin of about 10% and they are relatively insensitive to the variations of meteorological conditions. Consequently, they concluded that the two key parameters that control the effective efficiency are the series resistance and leakage conductance of the solar PV cell.

Suzuki (2002) carried out an analysis of loss factors affecting power generation efficiency on Multi crystalline solar PV modules. They reported that the variation of power generation efficiency with time can be estimated by separating the influence of solar irradiance and incident angle of direct and diffuse solar irradiance.

Amin & Lung (2009) studied the practical performance characteristics of various solar cells under Malaysian weather based on module efficiency and performance ratio analysis. Two categories of solar PV cells were tested namely: Crystalline category (Mono and Multi crystalline) and the thin film (Amorphous silicon and Cadmium Indium Selenide). They proposed mathematical expressions for calculating module efficiency and performance ratio. Finally, the module efficiency and performance ratio of each solar cell technology was compared by using experimental data and gave useful results. It has been reported that crystalline solar cells perform better under hot conditions while the amorphous solar cell perform extremely well with diffuse radiation and under cloudy conditions. The results show module efficiencies of 2.23%, 6.87%, 5.14% and 3.99% for amorphous silicon, Mono crystalline, Multi crystalline silicon and Cadmium Indium Selenide respectively. However, the authors argue that the conversion efficiencies are lower than those published by manufacturers and those generally accepted in literature, which relate to higher considerations. They attribute the differences to environmental effects such as solar intensity and temperature which influence the performance of solar cells. Moreover, the performance ratios were found to be 1.046 (Amorphous silicon), 0.933 (Mono crystalline silicon), (0.941) Multi crystalline silicone and 1.094 (Cadmium Saima) where the performance ratio denotes the ratio between actual yield (i.e. annual production of electricity delivered at AC) and the target yield (i.e. annual energy production on the DC side of the module) of the system. The performance ratio is independent from the irradiation and therefore useful to compare systems. Also, it takes into account all pre-conversion losses, inverter losses, thermal losses and conduction losses. It is useful to measure the performance ratio throughout the operation of the system, as deterioration could help pinpoint causes of yield losses.

Nkhonjera (2009) developed a model to analyse the performance of a Battery Based Stand-Alone Photovoltaic Systems for Malawi. The TRNSYS simulation model was used to simulate and analyse the performance of BSPVS based on system dimensions according to guidelines stipulated in Malawi Bureau of Standards. The model was validated by actual measured data under Taiwan conditions. It is reported that if the solar Photovoltaic system is designed according to Malawi Bureau of Standards, it is capable to operate at a mean performance ratio of 0.68 and system efficiency of 78%.

Tiwari & Sodha (2006) developed an integrated photovoltaic and thermal solar system to predict the thermal efficiency of solar PV module. They evaluated the performance of a PV module with an air duct in which thermal and electrical energy were produced together. Thereafter, an analytical expression for overall efficiency was delivered by energy balance equation. It was found that the thermal model increased the overall efficiency from 24% to 58% as a result of additional thermal energy due to water flow. The model was experimentally validated with values of average intensity of 670 W/m^2, temperature difference of 20 ^0C and collector efficiency of 50%.

Li & Lam (2007) developed a model for determining the optimum tilt angle and orientation for solar energy collection based on measured solar radiance data under the Hong Kong weather conditions. They have provided a numerical approach to calculate the solar radiation on sloped planes by integrating the measured sky radiance distributions. A developed model calculates the annual solar yields at different sloped surfaces facing various orientations and also calculates monthly solar radiations at optimal tilt surface and three vertical planes facing east, south and west were determined. Their results show that the optimum tilt angle for Hong Kong is around 20 ^{0}C due south and receives annual solar yield of over 1598 kWh/m^2. Additionally, they proved that solar collector with tilt angle approximately equal to the latitude of place is likely to receive maximum annual radiation. The multi crystalline silicone PV system performance was tested by TRANSYS simulation tool by tilting the system at optimum angle. The results indicate that high efficiencies were obtained in winter season due to low ambient temperatures and high energy output was obtained in October due to long sunshine hours and stable meteorological conditions.

Meyer & Dyk (2004) have conducted exhaustive experimental studies to establish photovoltaic degradation and failure assessment procedure on thin film and crystalline solar PV modules. They assessed different types of degradation modes by analysing performance of various parameters of solar PV module that include short circuit current, open circuit voltage, maximum power, ideality factor, series resistance, shunt resistance, saturation current and fill factor. The authors found out that the thin-film modules degrade by up to 50% in performance after an initial outdoor exposure of 130 kWh/m^2. Moreover, they indicate that physical inspection on both thin film and crystalline modules had shown cracked cells. They also say the cracks eliminated some cells from the electrical circuit hence reducing cell current production. In addition, the authors highlight the importance of characterizing all module performance parameters in order to analyze degradation and failure modes by observation.

In order to extract the maximum power point for a solar PV module, Balakrishna & et al (2006) studied and evaluated the main four types of maximum power tracking systems namely: perturbed and observe, incremental conductance, short circuit and open circuit. By using SIMULINK simulation results, they found that the only way to improve energy output, it is important to operate solar PV systems with maximum power point tracker (MPPT). The authors confirm that when an MPPT is used, the energy output from the solar PV increases by approximately 20% to 40%. In addition the authors found that out of the four methods of maximum power tracking systems, the incremental conductance method, though complex and difficult to implement, is able to work at the exact MPP with a working efficiency of 98%. Also, it performs well with changing radiation and temperature. They therefore concluded that the incremental conductance method is the best method in view of tracking the maximum power point.

Huld & et al (2009) proposed a simple mathematical model for the energy performance of solar PV modules as a function of in plane irradiance and module temperature. They validated their results by using data from three types of solar PV modules namely crystalline silicon, copper indium selenide and cadmium telluride in outdoor fixed installations. They indicated that solar PV modules may deviate up to 12% from the performance estimated from nominal power. Additionally, they had shown that performance of solar PV modules depends on geographical location and higher performance of solar PV modules is obtained in cold climates.

Based on the above solar PV modeling techniques, it can be concluded that the review has provided the author the appreciation of which are the most significant parameters that affect solar PV system performance and that can be monitored to enhance solar PV sustainability. It is the aim of this research study to compare some of the parameters under review to the technical parameters analyzed in the CRED project in order to assess the outdoor performance of mono crystalline solar PV modules under Malawian meteorological conditions. The parameters that have been monitored are the solar irradiation, short circuit current, state of charge, battery voltage (charging and discharging) and the resultant current between charging and discharging cycles. Additionally, the research study aims at demonstrating technical data gathering for solar PV in Malawi and at the same time compare the data with theoretical values.

Chapter 2 reviewed energy supply in Malawi and the problems associated with it. It also reviewed solar PV installations in SSA by citing a number of case studies that aimed at addressing shortage of electricity in remote rural areas. Finally, chapter 2 looked at the literature of various panel technologies, panel efficiencies and modeling techniques. The following have been the major findings:

The research study has found out that Malawi has chronic shortage of electricity. There is an imbalance between generation capacity and demand leading to regular load shedding schedules. It is therefore noted that with such unreliable power supply, it will be difficult to support the development of the country more effectively. Moreover, in recent years, there has been significant increase in electricity consumption by both industrial and domestic sectors that has compounded the problem of electricity supply. In addition, efforts to increase generation capacity have been absent or if anything have been minimal. Therefore, for the reasons mentioned above, the study has revealed that the extent of electrification in Malawi for urban and rural areas as compared with other SSA countries still remains relatively low at 7% thus leaving 93% of the population without electricity.

Furthermore, it is important to note that it has been found that in SSA solar PV system as a source of energy is well suited for remote areas and provide an effective complement to grid-based power, which is often too costly to meet. However, despite the that fact that solar PV has been recommended by many commentators as a means of alternative energy in provision social benefits to the users, the research study has found that solar PV programmes in SSA have failed to remain sustainable due a number of reasons such as poor system design, lack of financial support, unreliable technical performance, and lack of skills for operation and maintenance and unrealized user expectations.

Moreover, chapter 2 reviewed various panel technologies, panel efficiencies and modeling techniques, the following have been the major findings:

There are strong indications from various authors from section 2.7.3 that Multicrystalline solar cell still remains the most favoured for today’s photovoltaic technology despite its conversion efficiency being slightly below that of mono crystalline solar cell (Table 2.5) and the cost being higher than other panel technologies. It is specifically stated that the conversion efficiency of Multicrystalline solar cells are affected by recombination of active impurity atoms and extended defects such as grain boundaries and dislocations. Besides, it is indicated that there is still good potential that high efficiency on Multicrystalline solar cells can be achieved by controlling the temperature in ingot fabrication and cell processing in order to control the number and the electrical activity of extended defects.

In addition, it has been indicated that despite the setbacks of the Multicrystalline solar cell production aims at reduction of cost per watt peak so that solar energy can become competitive to conventional energies. It has been suggested that reduction in cost per watt peak can be achieved by simplification of ingot growth process by using cruder directional solidification or casting approaches to produce Multicrystalline ingots thereby reducing the thickness of the silicon wafer by slicing it more thinly (inner diameter sawing method). On one hand, thin film technology is more favored by electronics industry despite the fact that thinner silicon wafer has got high risk of breakage and cell bending, therefore care should be taken to maintain lower breakage rate.

Furthermore, it has been found that Multicrystalline solar cell efficiency can further be improved by controlling thickness, temperature in ingot fabrication and cell processing. Also the production cost for crystalline solar cell has potential to be reduced further. One of the keys for cost reduction is to reduce the silicon content of the crystalline solar product. However, from sustainability perspective, efficiency comes second to net energy because in some cases a more efficient cell will have a lower net energy over the same lifetime as a less efficient cell because of the energy needed to produce it. It is only valid to compare two solar cells by efficiency when they are made using the same fabrication process.

3 Chapter 3: Sustainability

This chapter opens by considering a brief overview of barriers that are a catalyst to low sustainability of solar PV systems. The section that follows looks at how some authors define sustainable energy development. Thereafter, special interest is paid to reviewing sustainability frameworks models for renewable energy systems such as solar PV prevailing in Sub Saharan Africa. In the final section, case studies that demonstrate low sustainability of solar PV systems are reviewed and the Community based approach to development of PV systems is introduced. The PV development in the CRED Project is assessed and available evidence is put forward for how the project contributes to filling of lack of performance data on solar PV system in Malawi.

3.1 Background

Schools and health centres in remote rural poor of Malawi often use solar PV systems to generate the electricity needed for services and staff. In most cases the solar PV systems work very well within the first two to three years after their installation and thereafter breakdown due to lack of repair and maintenance among other factors. However, it is important to note that sustaining PV system operation at these remote communities can be challenging. Various authors including Nieuwenhout & et al (2000) & Wolfe (2007) have echoed that reliable long-term operation requires that PV systems be well-designed and installed, using equipment of sound quality. In addition, the authors highlight the fact that institutional arrangements play a major role in system sustainability. It is said that institutional arrangements ensures uninterrupted recurrent funding for maintenance, repairs, component replacements, and spare parts. They also point to the fact that if any of these elements is lacking, done poorly, or done in ways inappropriate to the context, system failures can result. Correspondingly, it has been indicated Mabuza et al (2007 & Pablo & Unruh (2007) that in the past, technical reasons have often been cited for system failures. In some cases, it appeared easier to procure and install new systems rather than rehabilitate older ones. But such an approach, whose sustainability has depended on the chain of donor projects, is ultimately wasteful. It has been confirmed Mabuza et al (2007 & Pablo & Unruh (2007) that as the solar PV technology has matured, the confounding issues have increasingly centered on institutional factors, which are pivotal to project success or failure. In practice, this means that, during project formulation, greater attention must be paid to institutional frameworks and operational details for the post-project period (e.g. the running costs, ownership models, maintenance, and user controls). Consequently, in this chapter, sustainability will be clearly defined and case studies in Sub Saharan Africa demonstrating poor sustainability will be discussed. Also different sustainability models will be reviewed and finally the Community Based CRED model approach will be evaluated. The aforementioned topics will set out how solar power could be a sustainable and viable option for renewable energy supply. Moreover, how completed projects and on-going work in remote locations may lay the foundation for standards of excellence in this field.

3.2 Sustainable Energy Development

United Nations (1987) report defines sustainability as "meeting the needs of the present without compromising the ability of future generations to meet their own needs". The report further emphasizes that "Energy is a vehicle upon which the welfare of individuals, the sustainable development of nations, and the life-supporting capabilities of the global ecosystem depend". Moreover, sustainable development is concerned with distribution of resources between the present and future generations. Similarly, IIskog (2008) further argues that "economic growth and equitable distribution of resources that are derived from this growth are prerequisites for sustainable development. The growth must be of good quality, such as material and energy efficient, and be able to satisfy human needs such as health and education. The growth must not endanger the balance of essential ecological systems". The concept of sustainable development can be linked to electrical energy by what is called sustainable energy development and can be defined as "energy development that will require electricity services that are reliable, available and affordable for all, on a sustainable basis, world-wide". In conclusion, IIskog (2008) points to the fact that sustainability energy development for rural areas takes into account a holistic approach and centres on technical, economic, environmental and social progress and they are inter-linked. On one hand, the same author identifies the following major pillars/areas of sustainable energy development (Figure 3.1):

- Technical sustainability
- Economic sustainability
- Institutional sustainability
- Environmental sustainability
- Social sustainability

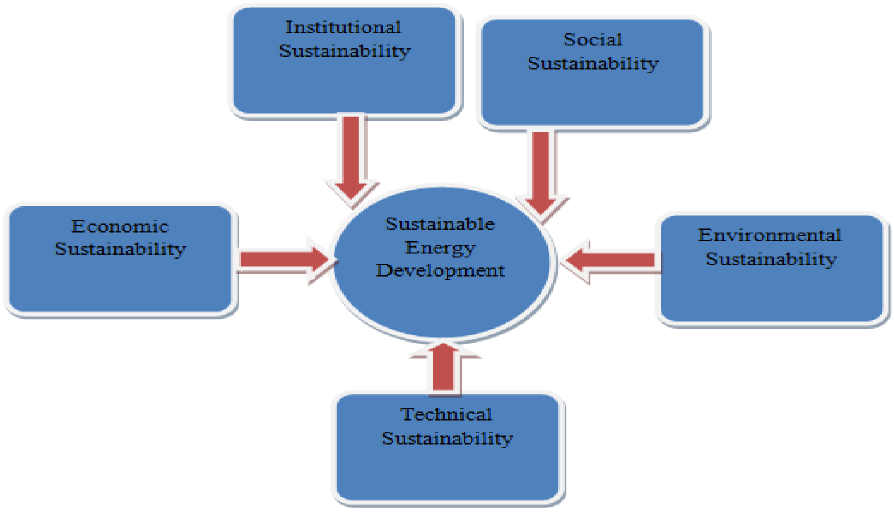

Figure 3. 1: Key Areas of Sustainable Energy Development

This illustrates the need for technological developments to remain aligned with the social, economic, institutional and environmental needs and constraints of poor rural communities. It is notable that the engineering approach must transcend simply the technical sphere when developing sustainable energy solutions. It is along this thinking that the various sustainable energy frameworks models should be designed to provide strategic approach to the development of rural energy solutions.

3.3 Sustainability Framework Models

Although most countries in Sub Saharan Africa have implemented rural electrification programmes, progress has been extremely slow and has not lived up to the expectation of the rural communities. Some commentators including Mabuza & et al (2007) & Pablo & Unruh (2007) have linked this to poor sustainability in terms of technical, economic, institutional and social deficiencies. A number of framework models have been developed to address the problem and find a lasting solution; and have been discussed in the paragraphs below.

Brent & Kruger (2009) highlight the fact that renewable energy projects deployed in rural communities are vulnerable to failure. The authors argue that there is a huge challenge in the way renewable energy projects are managed and highlight that meaningful sustainable energy development can only be achieved through participatory approach between society and renewable energy technology. In addition, Brent & Kruger (2009) have noted that amid challenges that contribute to failure of renewable energy projects are weak or inadequate regulatory frameworks, lack of financial mechanisms and political risks, inadequate institutional capacity to implement projects and lack of background knowledge of the renewable energy projects in relation to what is feasible on the ground.

Furthermore, a study on renewable energy models in Southern Africa indicate Brent & Kruger (2009) that the social and political factors play similar roles to economic and technical factors in terms of sustainability of renewable energy projects. Therefore, a holistic approach to renewable energy diffusion is a pre-requisite. In addition, Brent & Kruger (2009) recommend the Delphi framework model for assessment of sustainability of renewable energy projects because it provides a holistic approach in testing the sustainability of renewable energy project. It is indicated that the Delphi model engages experts from the renewable energy landscape and is a process that has a number of rounds where feedback is given to the participants between rounds after which they are given opportunity to modify their responses. Brent & Kruger (2009) point to the fact that the objectives of Delphi are two-fold: firstly it takes into account identification of possible factors that should be absorbed during selection of sustainable renewable energy projects and secondly prioritizing the factors in terms of the feasibility, desirability and importance of each factor. For example, the authors observed that the Delphi methodology tested in South Africa focused on the assessment of two renewable energy models to effectively address the ailments that were crippling the renewable energy sector.

Thus, the two framework models are: the Intermediate Technology Group (ITDG) and the Sustainable Rural Energy (SURE). The SURE framework model aimed at diffusion of the best technology option for rural areas. It is said Brent & Kruger (2009) that the SURE framework model aimed at suitability of the technology to the local rural communities. The model looked at assessments of energy services, environmental and resource, social development, economic and financial appraisal. On the other hand, the ITDG framework model developed a manual for rural energy and assessed environmental and resource, social development, economic and financial, energy service, institutional appraisal and development. The objective of the ITDG manual was to encourage participatory approach in the diffusion of the renewable energy technologies and to provide supportive institutions for sustainability of the renewable energy projects in the rural areas. Also the Delphi study was conducted as a litmus test for the two framework models in order to see if they were relevant and could be integrated in the South African rural communities.

In order to conduct the Delphi study, a group of Delphi experienced experts in the renewable energy were drawn to assess these two frameworks. An integrated framework that combined SURE and ITDG concepts was developed and recommended to be appropriate for remote rural areas because it took into account technological choice and appropriate strategy that looked at the holistic approach of renewable energy diffusion and thereby enhancing sustainability. The Delphi study framework raised two important points for sustainability of technologies that are deployed in the rural communities. Firstly, technological choice should always be a function of indigenous participation and structural arrangements and secondly it should take into account effective institutional arrangements for the benefit of the local people. Finally, Brent & Kruger (2009) recommend that it would be common wisdom that the Delphi model should always incorporate assessments of renewable energy framework models by applying sustainability science thinking.

In collaboration with the concept of the Delphi model, Rao & Kishore (2010) give more insight of technological diffusion for sustainable development of renewable energy technologies. The authors echo that diffusion of an innovation is a process of how, why, and at what rate new ideas and technology spread through cultures. Rao & Kishore (2010) argue that the diffusion of renewable energy technologies are driven by policies and incentives due to their inherent characteristics such as high upfront costs and lack of level playing fields (subsidies for conventional fuels) when compared to conventional energy sources. Moreover, renewable energy technologies offer energy security, have positive social impact and are environmental friendly. However, many authors including Brent & Kruger (2009) and Rao & Kishore (2010) arrived at a general conclusion that there has been limited realization of potential for renewable energy technologies despite their promotion for decades; only 20-25% has been so far realized. Thus Rao & Kishore (2010) confirm that diffusion analysis of renewable energy technologies has been entirely based on barriers to RETs adoption, integration of technical and economical, and learning experience cycles. On one hand, in order to mitigate on low sustainability and adoption of RETs, it is argued that diffusion analysis of renewable energy technologies should take into account policy issues that drive RETs diffusion. In addition, the relationship between the diffusion parameters and policies should be considered. Finally, Brent & Kruger (2009) and Rao & Kishore (2010) conclude that technology diffusion models for renewable energy technologies adoption hinge on five parameters, namely:

- Awareness - An individual is first exposed to an innovation but lacks information about the innovation. During this stage of the process the individual has not been inspired to find more information about the innovation.
- Interest – An individual is interested in the innovation and actively seeks information/detail about the innovation
- Evaluation - An individual takes the concept of the innovation and weighs the advantages/disadvantages of using the innovation and decides whether to adopt or reject the innovation. However, Rogers (1995) notes that it is the most difficult stage to acquire empirical evidence because the decision to try and adopt a technology is entirely dependent on an individual.
- Trial- An individual employs the innovation to a varying degree depending on the situation. During this stage the individual determines the usefulness of the innovation and may search for further information about it.
- Adoption- An individual finalizes their decision to continue using the innovation and may use the innovation to its fullest potential.

In conclusion, a review of different diffusion models by Rao & Kishore (2010) has shown that demand for RETs is created by governments and diminishing fossil fuel reserves; therefore it is the obligation of the governments to have attractive and deliberate policies for RET growth since RETs have a number of advantages over conventional energy sources such as their energy sources are abundant and in exhaustible, reduced environmental impact because generation of energy from RETs leads to reduced harmful substances being released in the air (CO_2) and their application is suitable for rural areas (also see section 2.1.2). And the diffusion model parameters should be adopted to reflect the issues of market potential, policy drivers and technological improvements**.**

Correspondingly, Rao & Kishore (2010) indicate that there is need for renewable energy framework models to prioritize assessable sustainability indicators for RETs that deem appropriate for the growth of RETs. In order to investigate the aforementioned, a technological model that is suitable for the African context was applied on the Lucingweni rural mini-hybrid off grid electrification system in South Africa. The framework model used the Kolb learning cycle that relies on conceptualisation, planning, experience and reflection. Rao & Kishore (2010) indicate that the Kolb Learning Cycle is a deterministic model that identifies a technology that will diffuse in the community based on economic, social, ecological and institutional sub systems through involvement of a panel of experts in all the fields. At a later stage, the experts review the indicators and priority is given to those which will enhance overall system sustainability. However, Rao & Kishore (2010) observed that the Kolb Learning Cycle model failed to work for the South African context because the intervention of the technology system did not provide adequate capacity and reliability for the renewable energy system and it proved insufficient to meet the expectations of the population i.e. provision of reliable and affordable electricity supply system. Moreover, various authors including Rio & Unruh (2005) & Brent & Kruger (2009) have indicated that RETs electricity energy is relatively new to remote areas of developing countries therefore adaptive capacity, management and resilience should be taken into account. Also governments should have political influence on all stakeholders to promote sustainable technology and socio-economic sub systems through incentives, subsidies and outright ownership.

The various framework models reviewed above illustrate the significance of incorporating sustainable framework models that can guide on how renewable energy technologies can be deployed in the remote rural areas in order to enhance system sustainability. Moreover, there is need to advocate a drive on renewable energy system analysis and continuous framework model assessment so that weak sections of the framework models can be identified and improved.

3.4 Barriers to Proper Diffusion of Renewable Energy Technologies

This section reviews some of the factors that hinder proper diffusion of renewable energy technologies such as solar PV and the factors can also be deemed to be recommendations made by various authors to enhance solar PV sustainability.

3.4.1 Lack of Conducive Financial Mechanisms

Available evidence shows United Nations Development Fund (2006) that there is slow adoption of solar PV system deployment in rural areas of Malawi. It is indicated that one of the major barriers to sustainable solar PV system deployment is the little support that end users are offered by financial institutions to adopt and use the technology. The financial institutions offer prohibitive conditions for financing solar PV systems for rural communities and stakeholders in Malawi. High interest rates on loans and full guarantee is required among others before disbursement of funds to the customer. The BARREM report highlights that in order to accelerate the adoption of solar PV systems in Malawi; the Credit Guarantee Fund (CGF) was established through the DANIDA Fast-Track project for local people to borrow funds for the purchase and installation of solar PV systems. The CGF was administered in conjunction with various banks and provided a 100% guarantee to participating banks, who then lent loans to customers. As a starting point, the customers were required to pay a 30% deposit. It is further reported that the responsibility of identifying and appraising customers was left in the hands of the contractor by using an application form developed by the Fund Manager. Thereafter, the contractor passed on the applicant's form to the Fund Manager who then authorized the loan and installation. Besides, the customer signed loan and lease agreement with the commercial bank through the supplier. However, it is reported that if the customer defaulted payment of the loan beyond the stipulated period, the Fund Manager authorized the contractor to repossess the equipment. In addition, the supplier had the obligation to pay the Fund Manager buy back value of the solar PV system. In this case, the supplier was expected to pay 50% of the outstanding loan value to the financial institution. It is concluded that the arrangement was retrogressive in terms of solar PV adoption and many contractors did not want to take a huge risk on their business.

This point above is sustained by the works of Turkson & Wohlgemuth (2001) who have observed that in Sub Saharan Africa and elsewhere, bilateral or multilateral organizations play major roles as financiers of solar PV projects. It is argued that a number of these solar PV projects are private enterprise and are not deliberate results from Government policies. While initial dissemination has been successful through government driven programmes, the long term functioning of the supporting structures built up has been poor. Additionally, it is argued that although attempts have been made to promote local suppliers and service capacity, most of the subsidies went to large entrepreneurs without sustainable operation once external financing ended. It is also observed that political pressure in the allocation of resources played a major role as well. Consequently, this resulted into being a catalyst of solar PV systems failure in Sub Saharan Africa.

3.4.2 Poor Quality Solar Products

United Nations Development Fund (2006) point to the fact that another setback to the slow adoption of solar PV systems in Malawi is that the market is flooded with poor quality solar PV equipment and materials. It is argued that it is the same poor quality products that are purchased and used for replacement and maintenance of solar PV systems. The effect has been frequent breakdown of solar PV systems once they have been installed hence affecting sustainability. However, a contrary explanation is given by Wamukonya (2001) who argues that solar PV systems are sourced from different parts of the world which makes governments monitoring and enforcement of standards difficult. Besides, United Nations Development Fund (2006) highlights that it is of great importance to adhere to standards of solar PV equipment because the purpose of standards is to ensure that the system is always available and operates with minimal downtimes.

Furthermore, BARREM notes that despite developing standards for solar PV in Malawi, the published standards MS695 and MS 696 are generalized, oriented towards larger systems, trigger high cost to the end user and are less impressive compared to Uganda (East African Standards) and South Africa (NRS standards) which have been accepted regionally and are considered for adoption by IEC. Moreover, BARREM noted the existence of a reasonable number of new, dynamic, certified solar PV providers and technicians in the country that have contributed to the development of solar PV system in Malawi however it bemoaned lack of consistence in carrying out quality installations. For example, some certified companies are carrying out solar PV system installations below the established standards. However Wamukonya (2001) argues that it is important that regional standards on solar PV systems should be used for sustainability of the technology. It is further argued that the presence of fake products and lack of specialized training for solar technician in the solar industry has grossly undermined the confidence of the local population and the survival of solar PV systems. And this problem, coupled with high initial costs and poor sensitization may lead to the complete collapse of the solar PV system in the near future. On one hand, Otieno (2003) observed that in Kenya unscrupulous suppliers have been overrating solar components for the sake of profits at the expense of the growth of solar PV industry consequently retrogressive for the public at large and Kenya. Many rural people lack technical skills on how to maintain solar PV systems. Consequently this has put solar PV system development and market in Kenya at the risk of collapsing. For example some suppliers are putting labels on imported solar panels wattage higher that the manufacturer. Additionally, practice of luring people to buy substandard products should be prevented and the government should step in to regulate the industry. Indeed, available evidence shows United Nations Development Fund (2006) that the situation in Kenya and elsewhere reflects that in Malawi.

Following the preceding paragraph that highlights the fact that poor quality products exist on the SSA renewable energy market, it is important to note that there are a large number of installers and suppliers of renewable energy systems in SSA. In this case adherence to technical standards for renewable energy technologies is crucial to sustainability. However, it has been observed that in SSA although technical standards for renewable energy installations exist, they only apply for small systems and for large installations the standards are almost absent. Nevertheless, in order to verify the quality of renewable energy products, Fraunhofer ISE with assistance from World Bank developed the International Electrotechnical Commission (IEC) 62257-9-5TS Ed.2 standards for testing Pico solar PV systems in developing countries. It is confirmed Erik (2012) that presently the aforementioned standards are being used in SSA. In addition, Erik (2012) specifically highlights that for Light Emitting Diode (LED) based solar Lights, different tests procedures are being carried out in the SSA to verify the quality of the LED based solar lights. The test uses the performance procedure of pass/fail criteria to eliminate poor quality products on each test level.

Moreover, the tests on LED based solar PV systems include detailed light measurements, electrical and mechanical measurements. However, it is said that conducting this kind of performance test procedure for LED based lights in developing countries has been a major challenge because of limited financial resources arising from inadequate budgets hence standards have been compromised. In this case some tests can not be carried out in accordance with international and national standards.

Furthermore, another policy and standard framework dimension advocated by SSA countries in order to enhance technical standards for renewable energy installations is do with capacity building and education. It is foreseen that deployment of technology without skilled human resource in charge of its own installation, manufacturing and maintenance is bound to fail. Therefore, SSA countries have taken an initiative to have comprehensive education and training programmes in order to equip people in the renewable energy sector to carryout installations and manufacturing processes according to the developed policies and standards. For example, once the people have been trained there is need for them to obtain a license for operation as experts in the renewable energy sector. In this case a person shall be allowed to design and install renewable energy systems when that particular person is registered by the commission that issues operating licenses.

Correspondingly, substantial body of evidence Kammen & Jacobson (2012) show that national standards for renewable energy equipment were formulated in the year beginning 1999 in Kenya. It is said that due to penetration of low quality renewable energy products on the Kenyan market, the Kenya Bureau of Standards (KBS) worked in collaboration with the Kenya Renewable Energy Association (KEREA) to draft performance standards for a range of solar products. It is specifically indicated that by 2003, the committee in charge of drafting the standards had approved a set of performance standards for both amorphous and crystalline PV modules that were derived from respective codes established by the International Electrotechnical Commission (IEC). The relevant IEC standard for crystalline silicon PV modules is IEC 61215, while the standard for amorphous modules is IEC 61646. The corresponding Kenyan standards are KS 1674 and KS 1675.

On one hand, it is confirmed Kammen & Jacobson (2012) that despite the fact that the renewable energy standards were established, the Kenyan Bureau of Standards did not have access to the necessary equipment or technical capacity to carry out the specified tests, and the standards. Moreover, although the standards were adopted, they were not enforced. Thus, Kammen & Jacobson (2012) highlight the point that while the move to draft and adopt performance standards may have represented a positive step towards an institutionalized approach to quality assurance, the adoption of un-enforced standards did little to protect the interests of Kenyan consumers.

In summary it can be said that most of SSA countries have developed minimum standards and installation guidelines for renewable energy equipment and installations. In actual fact these standards have been largely adapted from international standards and have been incorporated into National standards. It is for this reason that systems installed for government projects are required to follow these standards. Moreover, any equipment imported from overseas must meet these national standards. However, anecdotal evidence leads to the fact that most of SSA countries are not legally able to enforce their own national standards. For example SSA countries have little recourse with companies that bring in equipment that does not meet national/ international standards. Therefore, quality control has been a major challenge with regards to renewable energy equipment found in the market.

On one hand, private installations largely occur outside of any code or standards and there is no standard procedure for inspection of renewable energy systems. Therefore, promotion of awareness of standards might change the market status and perception of renewable energy as cheap technology that does not require following standard procedures.

3.4.3 Lack of Technician and User Training

Nieuwenhout & et al (2000) studied the experiences with applications of solar PV for households in developing countries and noted that there is not enough information available about the performance of solar PV for households in developing countries. For example in the Pacific, batteries in systems that are user owned and user maintained showed early battery replacements for two reasons: (1) systems are deliberately undersized in an attempt to get initial costs down; and (2) inadequately trained users or institutional poorly trained technicians usually replaced batteries without determining why the battery failed. Excessive shading, incorrect controller settings, improper panel orientation, excessive loads, wires too long or too small, appliance problems and poor connections can all cause real or apparent early battery failure. While replacing the battery appears to repair the system, in fact the new battery may also be doomed to a short life since the other problems persist. The authors argue that there are very few studies that describe in detail how solar PV systems are being used at household level. Additionally they conclude that the high failure rate at household level calls for more research to improve the quality of hardware and installation of solar PV system and consequently improve sustainability. There are some interesting correlations between studies by Nieuwenhout & et al (2000) and that of Wolfe (2007). The authors have observed that technical knowledge of how a solar PV system functions is of paramount of importance. The authors argue that the problem arises when the owners of the solar PV systems have no understanding of how the solar PV systems work and must pay local technicians for even the most minor faults. The long term effect was misuse of the system by the majority of the people and resulted in the people paying heavily on maintenance and repair of their solar PV systems. However, Wolfe (2007) singles out the battery as the most common problem that was vulnerable to gross overuse. The owners of solar PV systems were not educated on the basic principles of battery maintenance and were not aware of the limitations of the system. For example, electrical loads were routinely left on until their battery bank fully discharged and their appliances cut off. Then, without knowing the consequences of consistently over-discharging batteries, this practice was repeated until the battery electrolyte was depleted and could no longer hold charge. While this is the eventual fate of any rechargeable battery, understanding safe discharge limits can double or triple battery longevity consequently improve sustainability of the solar PV system.

Reiche & et al (2000) studied the impact of expanding electricity to remote areas in developing countries. The authors argue that off grid rural electrification such as hybrid wind and solar PV system can provide power for domestic uses such as lighting, cooling, TV, radio, communication, and for productive uses such as water pumping, fencing, cooling, mills, sewing machines and for public uses such as schools, health stations and police stations. However, they observed that lack of training Reiche & et al (2000) by the users and technicians on solar PV system maintenance was a major threat to system reliability due lack of local technical support. Additionally, lack of components/accessories of solar PV systems greatly reduces the acceptability of the technology to the users since the users cannot buy and maintain their system when required. Reiche & et al (2000) echo that for renewable projects to be more sustainable there is need to find innovative solutions for demand side, supply side, supportive financial mechanism and institutional strengthening. For example, for demand side, they literate that there is need to maximize local content. The more the local communities are integrated into the decision making process and the more ownership they develop and the more sustainable the project will be.

3.4.4 Lack of Government Deliberate Policies to Promote Renewable Energy

Islam (2001) reviewed the government of Bangladesh energy policy formulation and institutional development processes for exploiting renewable energy sources. The author studied the Draft Energy Policy of 2004 and 2005 and found out that there are several barriers hindering the wide spread deployment of renewable energy sources. For example, institutional, technical, information, human resource, policy barriers among others were singled out. Furthermore, he noted that the importance of renewable energy sources was not duly recognized in the energy policy. The author recommended that data analysis, planning methodology and thinking process need to be part of the package of renewable energy programme under the framework of national energy policy. The same author literates that pro-active and long-term policy-oriented renewable energy programmes aimed at senior decision-makers in both Government and the private sector should be initiated. Moreover, Islam (2001) indicates that the policy programmes should be designed to demonstrate the economic and environmental benefits of renewables technologies and propose short and medium term policy initiatives that would engender large-scale dissemination of renewables. Priority should be given to highlighting the real and tangible economic benefits (such as job creation and income generation) that renewable energy programmes can deliver to the developing countries at both the micro and macro levels.

As is emphasized throughout this thesis, well-designed renewable energy projects that increase the availability of energy services can amplify opportunities for productive work and income generation and thereby improve livelihoods. This section stressed the importance of designing and undertaking renewable energy projects with the right approach so that the renewable energy industry in Africa can become a major player in the energy sector, and meet the energy needs of a significant proportion of the population. Therefore, aggressive approach that takes into account the barriers in design and implementation of renewable energy projects is desirable so that the systems remain sustainable.

3.4.5 Summary of Sustainability

The sections above illustrate that renewable energy sources such as solar PV installed and applied in remote areas can assist in achieving Millennium Development Goals such as in education, health and reduction in poverty. However, factors such as: appropriate finance mechanisms, adequate means of providing regular and proper maintenance, timely supply of spare parts, lack of technician training, lack of user training (including women), lack of solar PV data bases, lack of deliberate policy to promote renewable energy, and theft and vandalism affect the sustainability of the solar PV systems. Therefore, the works of the above authors including Reiche & et al. (2000); Nieuwenhout & et al. (2000); Islam (2001) & Wolfe (2007) and the results of the cited projects highlight some key areas of consideration for sustainability of solar PV systems. Technical, economic and social aspects must be taken into account in technology diffusion. Based on this, it is clear that for solar PV systems deployment to have a chance of being sustainable it must consider more than just technical design but also institutional arrangements and continuous assessments of technological diffusion model frameworks must be carried out to refine sustainability.

It is against this background that a review of various works by authors above have shown that there is knowledge gap on how renewable energy sources such as solar PV are sustained and the review on sustainability sets out the areas where this research study will add to the knowledge on sustainability of rural electrification via solar PV programmes. In this research study, the

Community Rural Electrification and Development (CRED) model approach will be reviewed with respect to the sustainability problems that are associated with solar PV in Malawi. It is envisaged that the findings will add to the knowledge on solar PV sustainability and improve the evidence base for investment decisions on solar PV at micro and macro levels. In addition, the findings will assist planners to take into consideration the sustainability factors that need to be incorporated for good performance of solar PV in remote rural areas or on how solar PV programmes should roll out. Furthermore, substantial evidence has shown United Nations Development Fund (2006) that renewable energy projects such as solar PV lack a data base for project information which is extremely valuable to improve design of new projects. In order to add knowledge to solar PV system sustainability, the findings in this research will demonstrate how data can be captured and recorded with project information through a community managed solar PV system.

3.4.6 Life Cycle Assessments of solar PV systems

This section reviews Life Cycle Assessment of renewable energy systems. It is a well known fact that life cycle assessment of renewable energy systems such as solar PV plays a major role in measuring environmental and resource sustainability. Indeed there have been deliberate efforts by governments and the private sector in SSA to invest enormously in solar PV power. Anecdotal evidence indicates that economies of scales and improvements of material utilization and process and coupled with module efficiencies have contributed significantly in the reduction of production costs and environmental impacts. Therefore, this section will look at a full lifecycle analysis, energy balance, material resources, life cycle cost and recycling lifecycles of solar PV systems.

3.4.6.1 Full Life Cycle Analysis

Life Cycle Analysis is defined as a method aimed at evaluating the environmental burden of a product, a process or service throughout its whole life cycle, from the extraction and processing of raw materials, to its final dismantling, recycling or disposal. Indeed, available evidence shows Peng et al (2012) that the full life cycle analysis of solar PV begins with the extraction of raw materials and finishes with either disposal or recycling and recovery of the solar PV components. Of course, this involves several stages in order to obtain silicon of high quality. The first stage involves mining of the raw materials to extract impure silicon and the second stage involves processing and purification of impure silicon to obtain solar grade silicon through modified Siemens process. However, it is the purification processes that consume significant amount of electricity. It is also said that metal cadmium and tellurium and also indium and gallium which are used in the manufacturing of thin panel technologies are obtained through this process as by products. In addition, raw materials needed for solar PV systems are those that deal with encapsulations and balance of system components. For instance, silica for glass, copper ore for cables, iron and zinc ores for mounting structures.

Another stage in the full life assessment of solar PV systems is the one that looks at the support structures of solar PV systems. Deployment of solar PV systems incorporates erection of support structures, mounting of PV modules, cables and power conditioning equipments. Therefore, at the end of their life time, solar PV systems are decommissioned and system components are either disposed or recycled.

3.4.7 Solar PV Materials and Recycling

Solar PV systems are comprised of parts that can be recycled. Some of the materials that can be recycled include semiconductor materials, glass and certain metals in the group of ferrous and non-ferrous. It is these materials derived from end of life solar PV that are being recycled and taken back for use in the industry. However, it has been confirmed Brouwer et al (2011) that recycling possibilities depend on the kind of technology used in solar PV systems. For instance, it is said silicon based modules which are made of aluminium frames and junction boxes are usually dismantled manually at the start of the recycling process. Moreover, it is indicated Brouwer et al (2011) that more than 80% of the materials can be recovered by using flat glass recyclers. Also, it has been highlighted that the recycled glass can be used in glass foam and insulation industry.

Furthermore, other recycling technologies in use today are chemical baths. These technologies have the capability of separating different types of semiconductor materials. It is indicated Palitzsch (2013) that in order to separate various ingredients of the thin film panel technologies such as Cadmium Telluride, the recycling process takes into account crushing of the module initially and then separating the various ingredients contained crushed mortar. This method is said to have the capability of recovering up to 90% of glass and 95% of the semiconductor materials.

3.4.8 Energy Balance

Alsema (2000) estimated that silicon based modules that comprise Multicrystalline and Monocrystalline have primary energy consumption of between 2,400 MJ/m^2 to 7,600 MJ/m^2 and 5,300 MJ/m^2 to 16,500 MJ/m^2 respectively. The differences in energy consumption were attributed to different assumptions and allocation rules for modelling the purification and crystallization stage of pure silicon. On one hand, by collection of material inventory data from industry, Alsema (2000) has shown that the life cycle primary energy and greenhouse gas emission of complete rooftop for silicon PV systems are lower than those reported in earlier studies of similar nature. Alsema (2000) specifically indicates that the primary energy consumption for Multicrystalline and Monocrystalline are 3,700 MJ/m^2 and 4,200 MJ/m^2 respectively.

Pacca et al. (2006) reported that primary energy requirements for manufacturing thin film modules ranged between 710 MJ/m^2 and 1980 MJ/m^2. It is also indicated that despite the fact that the energy required for manufacturing modules is more depended on the modules' area, the manufacturing energy normalized by power output. Thus it has been confirmed Pacca et al. (2006) that while the manufacturing of 11.3 % efficient Monocrystalline solar module requires 9,638 kWh/kWp of electricity, a 10.3% Multicrystalline solar module requires 12,723 kWh/kWp of electricity. Moreover, at Standard Test Conditions (i.e.1,000 W/m^2 of solar radition), it is said that the power output values for Monocrystalline and Multicrystalline solar modules would be equivalent to 3,904 MJ/m^2 and 4,718 MJ/m^2 respectively. In conclusion, Pacca et al. (2006) highlight that the primary energy input into the manufacturing determines the energy payback time of the modules. In this case, the higher the input primary energy the longer the pay back time and vice versa.

Chow & Ji (2012) investigated the environmental life cycle analysis of hybrid solar Photovoltaic/ Thermal (PV/T) systems for use in Hong Kong. The authors evaluated the Energy Payback Time (EPBT) and the greenhouse payback time of free standing and Building Integrated PV (BiPV/T) systems. The EPBT of the free stand and BiPV/T systems were found to be 2.8 years and 3.8 years respectively. The study had shown that a longer period of EPBT in BiPV/T than in the free-stand case was due to the vertical collector position as compared to the best angle of tilt, and also the differences in collector size and solar cell packing factor. On one hand, the authors highlight the fact that a shorter EPBT is expected if Multicrystalline solar cell modules were used in the analyses because of the lower energy consumption during the manufacturing process.

Furthermore, Chow & Ji (2012) found out that most of the manufacturing activities of products consumed in Hong Kong are taking place in the Mainland China and the greenhouse gases (GHG) emission factor can solely be derived from this location. In addition, the primary energy consumption for power generation and that for CO_2 emission rate for coal-fired power plant are 12.01 MJ/kWh and 24.7 g CO_2 (equivalent)/MJ respectively. Finally, they conclude that the embodied GHG intensity of the PV/T collector in this case is 0.297 kg (equivalent)/kWh cumulative energy.

An inverter is one of the power conditioning solar PV equipments that has the capability of changing direct current generated by the solar PV generator to alternating current to drive portable electrical loads. Available evidence shows Keoleian and Lewis (2003) that the fabrication process of electronic components such as structural components printed wiring board and the transportation of the inverter contributes to environmental emissions in the life cycle of the solar PV system. The study indicates Keoleian and Lewis (2003) that the inverter contributes 18% Carbon dioxide (CO2), 16% Lead (Pb), 11% Nitrogen Oxide (NOX), 4% particulates and 46% of the Sulphur Oxide (SO2) in the life cycle of the solar PV system.

Peng et al. (2012) investigated sustainability and environmental performance of PV-based electricity generation systems by conducting a comprehensive review of the life cycle assessment (LCA) studies of five different solar PV panel technologies including Mono-crystalline, Multi-crystalline, Amorphous silicon, Cadmium Telluride thin film (CdTe) and Copper Indium Selenium thin film (CIS), and some advanced PV systems. Peng et al. (2012) highlight the fact that CdTe PV system presents the best environmental performance in terms of energy payback time and greenhouse gases emission rate due to its low life-cycle energy requirement and relatively high conversion efficiency. On one hand, Monocrystalline solar PV system had shown poor environmental performance in terms of energy payback time and greenhouse gases. The authors attribute this fact to high energy intensity during the fabrication process of the cell. In addition, Peng et al (2012) confirm that the energy payback time and green house gases rate of thin film PV systems vary from 0.75–3.5 years and 10.5–50 g CO2 (equivalent)/kWh, respectively. Furthermore, the authors point to the fact that energy payback time of

Monocrystalline PVsystems vary from 1.7 to 2.7 years with greenhouse gases emission rate from 29 to 45 g CO2 (equivalent)./kW h.

3.4.9 Life Cycle Cost

Life Cycle Cost (LCC) is a methodology of evaluating the financial viability of a system. In this case it takes into account the sum of capital cost and present worth of the recurrent and replacement costs.

Mahjoubi et al (2010) investigated the economic viability of photovoltaic water pumping systems in the desert of Tunisia by using the LCC method. The authors compared the LCC of the Diesel Generator which was commonly used for water pumping in Tunisia and solar water Pumping technology. It said the capital costs that were taken into consideration for a solar PV system for water pumping included the PV array, motor pump and installation costs. The study had shown that the LCC of the diesel generator was higher than that of the solar PV water pumping system. At the time of the investigation, it was indicated that the LCC for solar PV water pumping system and using diesel generator were 0.3 USD and 0.6 USD respectively. Moreover, Mahjoubi et al (2010) point the fact that it is possible to use a photovoltaic water pumping system but an optimization of the life cost must be made by taking account of other parameters.

Indeed, study reviews of full life assessments of solar PV lead to the fact that LCA method is the best tool for assessing energy and environmental performances of solar PV systems. The merits of the LCA are two-fold: firstly it provides a means of evaluating existing and emerging technologies and secondly it provides a means employing best practices to enable up scaling of solar PV systems. Moreover, LCA is seen to have provided powerful guidelines for a more efficient design manufacturing and application of renewable energy technology. Also the reviews point to the fact that designers and implementers of solar PV systems should be mindful of the energy content of materials in order to reduce carbon emissions and energy pay back time. Above all, LCA ensures that environmental aspects of sustainability are well documented. Several results of LCA discussed in this section support this belief.

3.5 Case Study: Community Based Approach for Sustainable PV systems – CRED Project

Having reviewed how sustainability of solar PV system is defined, the objective of this section is to introduce the Community Rural Electrification and Development project (CRED) which focused on installations of solar PV in schools and health centres. The project aimed at demonstrating how the socio-economic and technical sustainability challenges of solar PV in Malawi could be addressed. Additionally, the CRED project aimed to work towards a best practice solar PV deployment model specific for Malawi. Following this brief review of sustainability principles, the results of the pilot CRED project will be presented and discussed in the subsequent chapter and the under listed questions will be used to demonstrate the CRED community based approach for sustainable PV systems.

(i) how was the CRED project established and deployed in the rural remote areas of Malawi?

(ii) what is the CRED project structure that supports the solar PV sustainability?

(iii) what are the social impacts of the CRED project?

(iv) what is the CRED project approach to solar PV system sustainability?

3.5.1 Introduction

The community managed solar PV systems in the CRED project have capacity of between 150 to 250 Watts per installation and comprise of seven installations that run through seven remote villages of Chiradzulu and Chikhwawa Districts in the southern region of Malawi. The solar PV systems have mainly been installed in health centers and schools and are funded by the Scottish Government's International Development Fund with project partners being University of Strathclyde, University of Malawi – The Polytechnic, GoM Department of Energy and rural communities. Two certified solar PV installation companies namely, ECOPOWA and Radio Link were involved in the installation of the systems following common standard design criteria and component choice in accordance to the Malawi Bureau of standards.

3.5.2 The CRED Approach to Sustainability

The CRED project design drew on the principles of sustainability underlying the integrated framework for sustainable energy discussed in the previous chapter and addressed each of the pillars of sustainability;

- Technical sustainability
- Economic sustainability
- Institutional sustainability
- Environmental sustainability
- Social sustainability

Given the nature of the renewable resource, the environmental sustainability of PV systems was assumed to be inherent in the technology. In this context, solar PV is perceived to provide obvious environmental advantages in comparison to the conventional energy sources, thus contributing to the sustainable development of human activities. Not counting the depletion of the exhausted natural resources, their main advantage is related to the reduced carbon dioxide emissions and air emissions or waste products during their operation. The CRED definition of the four other areas of sustainable development which this integrated methodology was used to address, are outlined below:

3.5.2.1 Technical Sustainability

The design process of the PV systems include assessing peak load, average daily load, solar resource, days of autonomy to determine the technical specification of the PV array, battery technology, charge control and inverter electronics. This design process is well established and described in detail in many texts. It is assumed that a high standard of technical design is a pre-requisite of technical sustainability but not necessarily guaranteed. The technical sustainability is equally influenced by ensuring appropriate use, correct maintenance and access to properly trained engineering support in the event of failures.

3.5.2.2 Economic Sustainability

The economics of PV are often discussed in terms of market based situations, investment recovery and general affordability. In this context the upfront investment for the PV system is assumed with the justification for subsidized investment generally provided by a requirement for improved education/health. Therefore, The subsidized investment refers to the fact that government school/health facilities are non profit making organizations therefore cannot afford to pay for installation costs of solar PV systems. In this case, subsidy plays a major part in promotion and increasing rural electrification access through RETs such as solar PV. On the other hand, subsidy should be provided to the poor to provide them with alternative source of energy so that the poor who are learning and accessing health facilities should be able to enjoy full benefit of RETs. Therefore, communities living in rural areas will certainly need cost reduction measures on the installation of RETs as an alternative source of energy. However, subsidies should be temporary in nature and should be evaluated on regular basis. In the CRED community based approach model, the subsidy was only for the installation costs and the CRED project has been designed to cover the post recurring costs through income generating activities that build up the system maintenance fund that would in turn be used to repair and maintain the solar PV system. Thus, CRED definition of economic sustainability centers on the post installation recurring costs.

3.5.2.3 Institutional Sustainability

For the CRED project, institutional sustainability concerns the organizational structures bearing influence on the local community. These include Government (particularly local government structures), health and education policy and administration and traditional village authority structures. Thus, there should be a deliberate health and education policy by the government on how governance and sustainability of community energy projects can be managed through several decentralized government structures to facilitate development processes. One of the key elements is that the policy should ensure that the decentralized governance structures be positioned to strengthen management and governance of the solar PV systems in the district and the country as a whole.

Experiences so far show that health and education policy can effectively contribute to sustainability of renewable energy technologies such as solar PV systems. It is a well known fact that in too many cases; users in areas where solar PV has been introduced soon learn that the claims of “maintenance free power from the sun” are not true. The operating performance of systems decline once they have been installed. This is attributed to a number of reasons including lack of skills and knowledge to maintain the broken down systems, end user unfamiliarity with system requirements such as limitation of system loading etc. Therefore, if there can be a deliberate policy by the government that the subject of renewable energy technologies should be taught in primary and secondary schools and institutions of higher learning, then an increased number of people in rural and urban areas will have skills and knowledge of renewable energy technologies. Therefore, assist in sustainability of renewable energy technologies.

Moreover, by providing energy to remote areas, renewable energy technologies improve rural health for refrigeration of medicine, equipment sterilization, and safe disposal of medical waste by incineration. Therefore, renewable energy technologies supplied electricity to health facilities enables the local community to be more responsible of their systems. The reason being the people using the systems will be central in maintaining the systems so that the improved quality of life that has been introduced due installed renewable energy systems is not lost. In this case, a deliberate health policy will lead to increased adoption of renewable energy technologies and at the same time contribute to system sustainability through community ownership.

3.5.2.4 Social Sustainability

Within CRED, this concerns the general interaction of the community with the PV installation, in particular its engagement, participation, ownership and the accountability of the local users. The proposed approach to achieving sustainability in these areas is based on community focused system design and a community ownership model. These two core aspects of the sustainable model and the 'influence links' to the key sustainability areas are illustrated in Figure 3.2

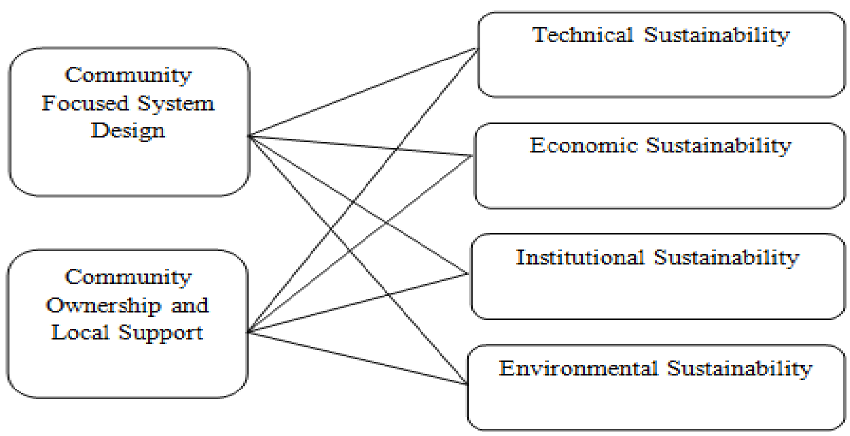

Figure 3. 2: Community Based Model

3.5.3 Community Focus

As demonstrated above, the CRED exploration of the pillars of sustainable energy mapped to two main areas of focus for the design of the project. These are discussed in the following sections.

3.5.3.1 Community Focused System Design

Standard practice has been to design a PV system for the core requirements of a school or health installation, directly benefiting the users of these services. The CRED approach was that system design must be viewed from a wider community perspective to maximize potential benefit and exploit income generation opportunities. Inputs to the design process included: PV system design standards, locally available technology, budget, core load requirements, additional load implications of wider community use and any income generation activity.
Technical sustainability is influenced by standards based design and the use of locally supplied technology for ease of maintenance. Economic sustainability is influenced by the design to allow for income generation with minimal additional infrastructure. Social sustainability is influenced by design to maximize participation and access to the wider community.

3.5.3.2 Community Ownership

Positioning the electrical system as a community resource allows for greater engagement and participation from the wider community. Although health and education facilities are owned by the responsible government agencies it is common practice for local communities to play an active part in sustaining and maintaining these facilities. The CRED approach fosters a sense of ownership which encourages the community to recognize the electrical infrastructure. While the PV system may not be the legal property of the community it should be regarded as a resource that improves the lives of the community, and which will deteriorate and fail without their care. The proposed model for community ownership was an Energy Committee. The committee would be formed through acknowledged local process and represented the community's responsibility for the maintenance, security and responsible use of the system. The committee was intended to work in partnership with the responsible health and education employees to ensure the core functionality was prioritized but that wider community access and income generation was promoted and managed in a coordinated manner. The CRED position was that appropriate community sensitization and training is central to establishing a functional energy committee.

A key CRED principle was that the success of the local energy committee is the support that is available to them for technical support and ongoing knowledge transfer. In addition to the need for additional training, the energy committee will need regular refresher training, encouragement, and perhaps an incentive, to actively fulfill their roles. In the event of technical failures, the committee will also require trusted advice and access to maintenance engineers. The CRED intentions were that the energy committee influence technical sustainability by ensuring appropriate use, providing basic maintenance, security and recognizing the need for maintenance engineers. Economic sustainability is influenced by the committee assuming responsibility for income generation and the growth of a maintenance fund. Institutional sustainability is influenced by providing appropriate community representation working with the approval of education/health administration and traditional local authorities. A local representative formally taking responsibility for the system influences social sustainability as does the facilitation of wider community access. Local support is essential for technical sustainability in the event of maintenance issues. Continued knowledge transfer and capacity building of the energy committee influence the social sustainability.

3.5.4 Monitoring and Quantitative Data Capture

CRED took the view that monitoring and data capture should be undertaken throughout the project in order to assess progress and test the success of the proposed approach.

It was clear from previous lessons learned in the deployment of rural schemes that the benefits are only accrued when the systems are fit for purpose and used for the purpose for which they were designed. CRED proposed that quantitative and qualitative technical and socio-economic data gathered from the local communities and the region's educational directorate be collated. This was intended to provide an insight into the community-wide impact that community-owned systems can achieve for a given level of system investment and design standard. The data gathering was proposed to be ongoing and consider: examination results pre and post installation; analysis of each installations fault/usage log; the income generation subsidizing system and school maintenance from small phone charging businesses; information on battery charge/discharge cycles and consumption history. The intention for this data was to serve to optimize designs for user requirements.

3.5.5 Assessing System Requirements

A key approach to system design incorporated assessing the requirements through discussions with local teaching staff, clinic staff, village elders and the Parent Teacher Committee.

3.5.5.1 School schemes

With the aim of schools serving as community hubs where extended schooling, community meetings and evening recreation for the community could take place. System requirements were defined as; lighting for 2 classrooms and the head teacher / staff area; and power for mobile phone charging.

3.5.5.2 Health Post

The Health Post serves many of the surrounding communities and required provision of a medical refrigerator for vaccinations and lighting to conduct emergency procedures in the evening if necessary.

Indeed, as it can be seen from chapter 3, sustainable energy development would require a holistic approach that encompasses institutional, economic, environmental, social and technical sustainability. Additionally, technological choice should always be a function of indigenous participation and structural arrangements, and should take into account effective institutional arrangements for the benefit of the local people. However, it is important to note that technical sustainability should be given the highest priority since it would ensure continued operation of the system and support other strands of sustainable energy development. In this section, the methods taken by the CRED project to address these issues have been presented.

4 Chapter 4: Results and Discussion

This chapter presents the results for both technical and social sustainability of the CRED project to demonstrate the level of solar PV sustainability. Firstly, it starts by presenting the analyzed social results for the solar PV system. Thereafter, the presented social results are discussed. The subsequent section of the chapter reports on the technical results thereafter a discussion of the reported results is given.

4.1 Social Results

4.1.1 Social Sustainability

The social and economic results presented here are from a sample of sites of the CRED project; namely Malavi and Mikolongo sites. The results relate to income generation namely: mobile phone charging, battery charging and sale of cold drinks. Moreover, the impact of the CRED project on the rural population is assessed. It is important to note that prior to the electrification of the seven villages, interactive interviews and baseline study was undertaken and the results of the impact of the project are based on comparative analysis focusing on what has been the quality of life in these villages before and after the installation of the solar PV.

(a) Mobile Phone Charging at Mwanayaya CRED Site

Table 4.1 show the accumulated monthly collection of fees through daily mobile phone charging in this CRED site. The results show that for the months of October, November and December, there was significant collection of fees. Moreover, the results show that there has been in general an increment in collection of funds for mobile phone charging for each month. By the end of December 2010, the CRED site had collected funds amounting to MK45, 460.00 (£181.84) which was put in the bank account as funds meant for maintenance of the system. It has also been observed that the amount fees collected for each particular month entirely dependent on the number of community group activities that had access to the solar PV system. Thus, more fees were collected when there was high frequency of community group meetings for that particular month. For example, the months of October, November and December as shown in Table 4.1, the collection of fees is higher than the rest of the months. It is important to note that some of the community group meetings would lead to people spending one night or two at the school more especially over the weekend. Therefore, this would provide an opportunity for people to charge their phones and generate income in the course of patronizing the scheduled community group activities.

The other reason why charges per phone has been erratic is that energy committee members responsible for collection of phone charging fees were not recording the correct amount of fees for every phone that has been charged. It was observed that in some instances the price people paid for having their phones charged was as low as MK20 despite having a fixed price of MK50. This also contributed to the variation of fees collected for each month. It can well be said that theft of money by the energy committee existed in the course of collecting fees from phone charging.

Despite erratic collection of fees, this trend shows that the CRED solar PV system pivoted as community resource was being well utilized for the benefit of the local population. Indeed, the evidence is the continuous collection of daily fees emanating from charging of mobile phones.

Month	**Income from Charging Phones (MK)**	**Banked Funds (MK)**
Jan	3,100	3,100
Feb	1,900	5,000
Mar	1,760	6,760
Apr	1,620	8,380
May	1,200	9,580
Jun	1,420	11,000
Jul	2,040	13,040
Aug	2,060	15,100
Sep	2,140	17,240
Oct	7,220	24,460
Nov	10,280	34,740
Dec	10,720	45,460
Total (MK)		**45,460**

Table 4. 1: Monthly Phone Charging Record for Mwanayaya CRED site

(b) Evening Study at Mwanayaya CRED Site

Figure 4.1 shows that there has been increased numbers of students at school during the increased hours of study through school lighting systems. The statistics for a period of one year show that, on average, 138 students per month were attending the evening study session using solar lighting for an average of 3 hours per day. However, it is important to note that the students' attendance number was independent of available study duration hours the solar PV system provided per day. It can be seen that for the months of October and December, the students' attendance was low compared to the rest of the months. The teachers attributed the low attendance was due to the fact that many students during the months of October to December assist their parents in farming in the agricultural fields. Also, farming activity normally takes place in the afternoon hours and students then would be tired to go for studies in the evening. Despite the aforementioned fact, the provision of solar PV lighting in schools has the potential to attract students to study for extended hours. It has also been noted that there is potential significance of solar PV as not only as stimulant to quality of education but also to some extent an attraction to attend formal education for the population that is not attending education.

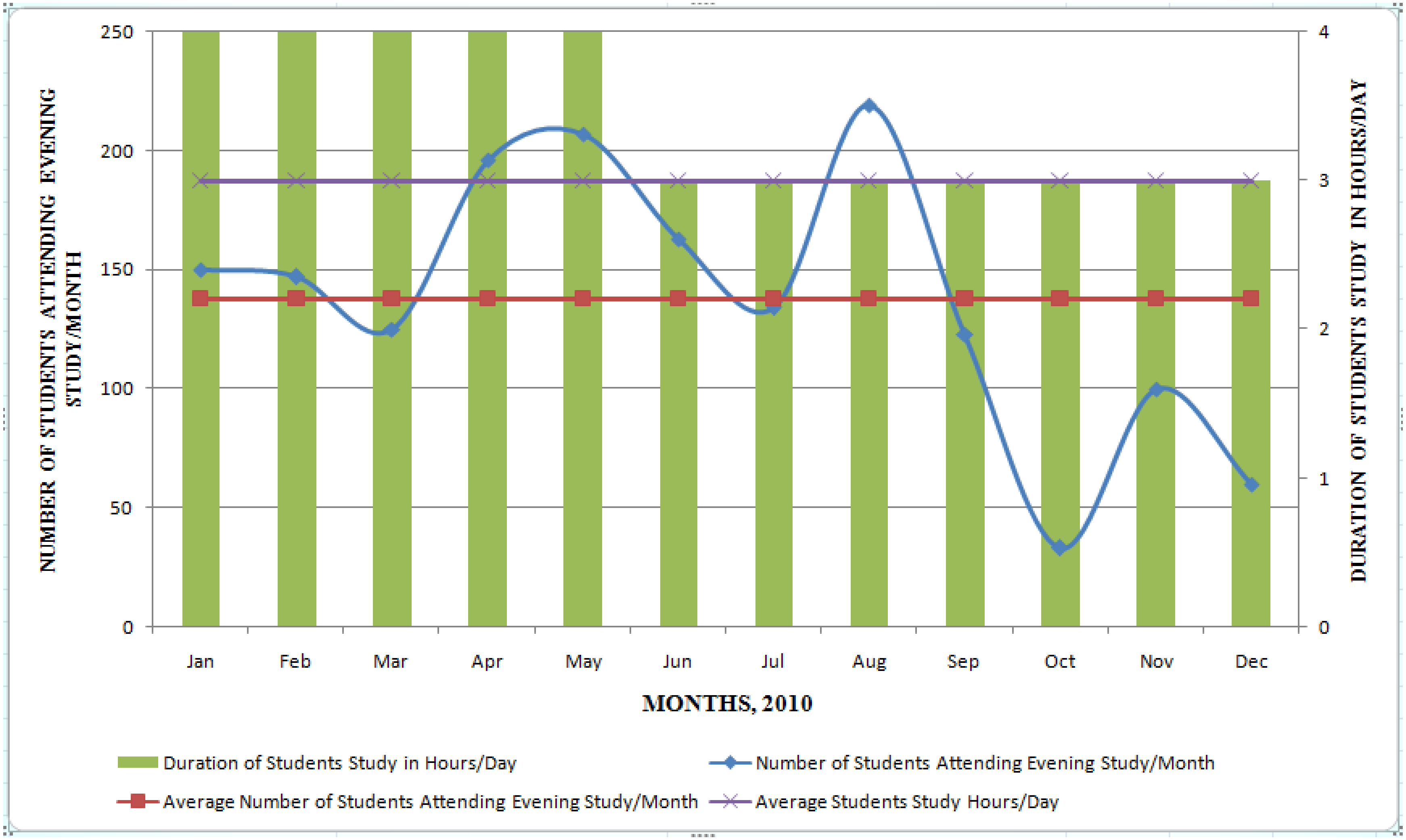

Figure 4. 1: Students Evening Study Attendance for Mwanayaya CRED Site

(c) Mobile Phone and Battery Charging at Malavi CRED Site

Table 4.2 show the result of mobile and battery charging at Malavi CRED site. The results show that MK36, 000.00 (£144) was realized from battery charging and MK8, 620.00 (£34.48) was realized from mobile phone charging for a period of one year. For the months of May, June and October, fees for battery charging were not collected due to a faulty inverter that resulted into loss of income. However, since certified installers were used in the installation of the PV system, they provided maintenance of the system and collection of fees resumed. However, it is important to note that during the same months, fees for mobile phone charging were collected. This was the case because the phone charging circuit is separate from battery charging circuit. Also, it was observed that the energy committee members could not account for mobile charging fees for the month of October despite the fact that the mobile phone charging service was functional at that time.

Nevertheless, the collection of monthly fees by the local people made them to be more responsible for their solar PV systems. It created ownership feeling and made them to be the owners of their village solar PV system. Moreover, it made them realize that the funds generated from the solar PV system were to be used for maintaining the systems. With these funds the maintenance, any repair or battery exchange, and salary cost for the trained maintenance person has to be covered. Therefore, the approach of collecting monthly fees from solar PV installations presents important steps towards higher appropriateness and sustainability.

Month	Charging		Banked Funds
	Phone (MK)	Battery (MK)	(MK)
Jan	780	4,000	4,780
Feb	440	4,000	4,440
Mar	220	4,000	4,220
Apr	800	4,000	4,800
May	720	0	720
Jun	360	0	360
Jul	700	4,000	4,700
Aug	1,000	4,000	5,000
Sep	800	4,000	4,800
Oct	0.00	0.00	0
Nov	1600	4,000	5,600
Dec	1,200	4,000	5,200
Total	**8,620**	**36,000**	**44,620**

Table 4. 2: Monthly Income Generation from Phone and Battery Charging and Banked Funds for Malavi CRED Site

(d) Sale of Cold Drinks at Namira CRED Site

Apart from using the solar driven refrigerator for storing medicine, the Namira energy committee members embarked on sale of cold drinks as part of small income generation in order to solicit funds for maintenance and repair of minor technical problems of the solar PV system. For example, the energy committee saved adequate funds to be used for replacement of burnt dc solar fluorescent lamps which cost around MK1, 500 (£6). Table 4.3 show that for a period of one year, MK13, 500 (£54) was realised from the sale of cold drinks. The funds would be sufficient to buy 9 dc 11 Watts solar fluorescent lamps in a year. Although the income generation has been low, the concept of saving funds for maintenance of the solar PV system amongst the energy committee members was developed and has been of paramount importance as already stated in section 4.1.1 (c).

	Sale of Cold Drinks				
	Money	Money	Total	Net Profit	Banked
Months	Invested (MK)	Spent (MK)	Sales (MK)	(MK)	Funds (MK)
Jan	1,810	1,810	2,500	690	2,500
Feb	2,500	1,810	2,500	690	3,190
Mar	3,190	1,810	2,500	690	3,880
Apr	3,880	1,810	2,500	690	4,570
May	4,570	1,810	2,500	690	8,520
Jun	8,520	1,659	2,399	740	9,260
Jul	9,260	1,659	2,409	750	10,010
Aug	10,010	800	1,200	400	10,410
Sep	10,410	1,600	2,340	740	11,150
Oct	11,150	4,150	6,000	1,850	13,000
Nov	13,000	1,900	2,400	500	**13,500**
Dec	0	0	0	0	0
Total		**20,818**	**29,248**	**8,430**	**13,500**

Table 4. 3: **Income from Sale of Cold Drinks for Namira CRED Site**

(e) Community Groupings

In the first place it should be made clear that this was evening study and was not baselined. Also in these communities there have been no solar PV installations before until when the CRED project was implemented. Therefore, evening study and meetings were absent before installation of solar PV. The results in Table 4.4 show statistics of various groups that were meeting in the evening in the seven communities where CRED solar PV systems were installed. There is indication that community groups had access to the use of the CRED solar PV systems. Moreover, the results have shown potential of community groups meeting regularly in the evening to discuss matters that affect their lives by using solar PV lighting. Correspondingly, in both surveys and interviews carried out by Picken (2010) and social and economic data collection from CRED project, highlights the fact that students' evening studies at Mwanayaya and Mikolongo schools was absent. However, with the installation of solar PV systems, there have been significant numbers of students attending evening studies. Therefore, it brought the students' increased ability to study in the evening.

At the time of writing this thesis, teachers and energy committee members mentioned that the number of days for students evening study at school was absent. However, it was said that when students were about to write their end of year examinations teachers would encourage students to read in the evening by using kerosene lamps in their respective homes. However, teachers were unable to come up with statistics to support the fact that students were reading in the evening in preparation for their examinations. However, with installation of solar PV in schools, it has been observed that the students evening study days has been 782 for a period of one year (i.e. for seven villages) and 10,730 students have been recorded to have attended evening study sessions. Moreover, the study duration has been one hour to three hours per day.

On one hand, teachers and energy committee members highlighted that two groups were meeting occasionally during the day before installation of solar PV and the groups include Parents and Teachers Association (PTA) and the school committee. However, after installation of solar PV these groups have been meeting in the evening and it has been noted that 11 groups have been meeting in the evening. Besides, it has been noted that the number of people who attended evening community group meetings total to 5,401 for a period of one year. Furthermore, the groups that have been meeting include church committee, village development committee, health committee, youth clubs, football committee, business committee, solar energy committee, security committee and many more. It is the author's opinion that such meetings created a conducive environment for local people to discuss developmental issues through an implemented solar PV project. The development issues include improved income generation possibilities, evening non-formal education classes for adults, community gatherings, dissemination of useful information to the public from the private sector, government and NGO's just to mention a few.

Description of Item	Before Solar PV Installation	After Solar PV Installation
Students' Evening Study Days	0	782
Number of Students	0	10,730
attended evening studies at school		
Average students study hours/day	0	3
Number of community groupings	0	11
Number of people attended community	0	5,401
groupings		
Total income from income generation activities (MK)	0	128,849

Table 4. 4: Social Data for Seven CRED Sites: Source Interviews with CRED Energy Committee Members (2010) and CRED Report (2010)

4.1.1.1 Socio-Economic Impact of the CRED Community Based Project

By conducting interviews with the stakeholders (local community), detailed analysis of the socio-economic data and author's own observation, various ways have been revealed in which solar PV has been socially and economically beneficial, particularly through its use within the first three years of the CRED project inception. The associated impacts are discussed in this section. The discussion is focused on activities that include income generation, communication, education, health and environment, communication through Information Technology (IT) and community groupings.

(a) Income Generation

Apart from provision of lighting the CRED project has ventured in income generating activities through mobile phone and battery charging and sale of cold drinks by using DC refrigerators. For the year ended 2010, approximately 130,000 Malawi Kwacha (£520.00) was collected through phone charging and sale of cold drinks (Table 4.4) from all the CRED centres. In some centres a monthly flat rate payment for the use of the system was introduced to cover for maintenance and operational costs. With regard to the latter each connected teachers' house has been paying a monthly tariff of 500 Malawi Kwacha (£2.00). For example, at Malavi School four teachers' houses generate a monthly income of 4,000 Malawi Kwacha (£16.00). It is important to note that electricity usage is not metered however using teacher estimated lighting and radio use provides an approximate average use of 2.43kWh in one month. This equates to indicative 205 MK per kWh. In the year 2010, the total revenue collection from teachers' houses at Malavi for a period of 9 months amounted to 36,000 Malawi Kwacha (£144.00) (Table 4.3). In theory the annual revenue paid by teachers would be sufficient to pay for the cost of a new deep cycle discharge solar battery. Also, literature shows Dunlop (1997) that for a well maintained solar PV system, the battery life can go beyond a period of five years. It can been calculated that for eight teachers' houses that have been installed with one battery, the total generated revenue for one year would be equivalent to MK48, 000 (£192). Over a five year period, the total revenue would translate to MK240, 000 (£960). Since the current market value of a solar battery is MK30, 000 (£120), it means the total collected funds over five years would enable the purchase of eight batteries. Moreover, if fees for the use of the system were to be raised to MK1, 000 per month for each of the teachers' houses, which is affordable for teachers, then the revenue collected would double the number of batteries to be purchased over the same period.

These results indicate that a school system with teacher based revenue and mobile phone income generation is financially sustainable as funds would more than cover worst case expected maintenance cost over a period of five years. Of course the revenue analysis can only be expected to cover on-going running costs and recovery of installation costs is not feasible.

Figure 4. 2: Community Energy Committee formed to Manage the solar PV system

Figure 4. 3: Provision of Solar Lighting in One of the CRED centres

(b) Effective Communication

Most remote rural schools have problems with communication with their local education headquarters or higher administrative instances. This makes their task of educational reports or report follow up with local educational headquarters more difficult. It has been observed that solar PV system is an enabler for effective communication amongst people and organizations. The CRED solar PV system installed in seven remote rural villages in Chikhwawa and Chiradzulu Districts has brought substantial effect in terms of communication amongst individuals and organizations within and outside the area. For example, teachers communicate effectively with the local headquarters as they discharge their daily duties. In the past teachers would charge their phones some distances away overnight and resume communication the following day. But since they can charge their phones during the day with solar PV system, it has been observed that the delay in communicating vital information to the local headquarters has been greatly reduced. Currently, significant numbers of phones are being charged on daily basis which is a sign that the local community is able to communicate more effectively in their day to day business engagement than before. It has brought a communication revolution in this area. Currently, more than 250 mobile phones are being charged per month.

(c) Improvement of Health and Environment

Most basic healthcare facilities in Malawi are owned by the Government and managed by the district hospitals. These healthcare facilities are mostly situated in rural areas without electricity. Because of their sizes and scope of activities, functioning mainly by day and carrying out no major medical operations, these healthcare facilities are candidates for standalone solar PV. It is along this background that the CRED project core functionality was to provide the health posts with lighting in the treatment room and vaccine refrigeration. Again, additional lighting was included for community purposes and mobile phone charging provided for. It has been observed that with installation of solar powered dc refrigerators (Figure 4.4) that store refrigerated drugs and vaccines, women access immunization for their young ones within an easy walking distance thereby saving adequate time to do other productive activities at their households. Additionally, the distribution of solar home units for lighting purposes at subsidized cost, has greatly improved internal home and work environment. The risk of dangerous smoke and soot associated with the use of kerosene lamps in homes and health care centers has been eliminated. The health risks have been reduced and health related costs have also been lessened. Consequently assist in the improvement of quality of health.

Figure 4.4: Comments from Alexander Chiwanda – Health Surveillance Assistant at Mwalija Health Post

“I now have extended time to attend to my patients at night which was not the case when solar electricity was not implemented at the health centre. Apart from solar electricity assisting in storage of refrigerated medicine, it has enabled us to run small scale income generation activities such as selling of cold refreshments. Source: Interview by author (2010)

Figure 4. 5: Comments from Jeffrey Zingaloti – A Student at Mikolongo Primary School in STD 7

"As learners of Mikolongo School we get advantage of the solar energy provided by CRED project in the following ways:
We don't spend money on buying paraffin/candle that produce poisonous fumes for studies and are prevented from respiratory diseases. Also
It encourages us to have extra discussion sessions amongst classroom groups in the evening and Our teachers assist us during study time by teaching and marking our assignments." Source: *Interview by author (2010)*

(d) Improvement of Communication through IT

Mobile phone companies in Malawi spend a lot of money creating business and market for their products. Therefore, they invest heavily on their telecommunication network in order to have wide network coverage and increase customer base and eventually maximize profits. Moreover, their mobile based stations are located in many parts of the country and are usually positioned on high grounds. Also the mobile based stations are powered by either ESCOM or a diesel generator since ESCOM power is unreliable. However, mobile power locations for mobile phone companies are not accessed by the local community for provision of lighting and power to drive portable electrical appliances. Therefore, besides provision of lighting in remote rural areas, the most important use of solar PV electricity in schools is the powering of Information and Communication Technology (ICT) hardware i.e. computers, their peripherals and networking hardware as well as other teaching/learning aides. Thus availability of solar PV at one of the CRED centers - Malavi has seen teachers getting connected to the internet. The Internet at Malavi has played a vital role by giving students and teachers an extra resource for obtaining, storing and transmitting information, for teaching and learning. For example, currently teaching staff at Malavi School are able to send and receive vital information through emails from their counterparts within Malawi and partner schools in Scotland. Also students are acquiring hands-on learning skills on two lap top computers that have been put in the school library. A small group of five students have been learning computer skills on rotational basis almost on daily basis. For this reason, students and staff may improve the quality of their lives as well as that of the community and at the same time make great contribution to the economy of the nation.

(e) Improvement in Quality of Education

In Malawi primary education is almost entirely in state hands both by ownership and control. Most of the primary schools are located in rural areas without grid connection and there is no prospects for grid based electrification in the near future. Therefore installation of solar PV for teaching/learning and administrative activities in these remote rural areas will make a significant difference. In the case of CRED project, the core functionality required by the school was evening lighting. Additional evening lighting was included for community purposes. A low powered inverter was included to allow mobile phone charging. It has been observed that solar PV electricity in these remote rural schools attracted (Figure 4.5, Figure 4.6 & Appendix 7) students to study in the evening and teachers to plan for their teaching activities thereby achieving primary education. One of the teachers at Mikolongo, Mr Chilenga Mkhuphuki, remarked that teachers and students have evening learning sessions due to solar lighting at their school while on the other hand; teachers and students in the surrounding neighbourhood do not hold evening studies because of absence of solar lighting. The two cases hold a significant difference in terms of knowledge building amongst teachers and students. The results in Table 4.4 show that a total of 782 evening study classes were conducted reaching more than 10,730 students for the year 2010 in all CRED sites.

Figure 4. 6: Comments from Mr Chilenga Mkhuphuki – A teacher at Mikolongo Primary School.

"The installation of solar electricity at our school by CRED has had significant impact on me as a teacher. Before the introduction of CRED project I had difficulties in continuing making lesson plans and schemes for my classes in the evening. However, life has completely changed now because I can use solar electricity in the evening to prepare for my lesson plans and schemes for my classes and to light my studies. The school pass rate has also improved when compared to the previous years. We also do phone charging that helps in continuous communication amongst ourselves. I recommend it from deep down in my heart: it is reliable, cheap and long lasting. We haven't had any major problem as a school in the course of using the CRED facility."I Source: Interview by author (2010)

(f) Community Groupings

The solar technology has encouraged people to be meeting regularly in the evening in the locations where CRED solar PV systems have been installed to discuss matters that affect their lives. It was indicated by the stakeholders that some groups were unable to finish their business discussion during the day but because of the presence of solar lighting, the groups were able to finish their remaining discussions in the evening. The results data show that 11 community groups were meeting regularly and more than 5,000 people attended these community meetings in the year 2010 (Table 4.5). The community groups that were meeting have been outlined in section 4.1.1.1

(g) Summary of the Socio-Economic Impact of the CRED Project

Table 4.5 gives an overview of the socio-economic impact of the CRED project. An interview by various stakeholders that utilized the solar PV system responded in one way or the other that the solar PV system was beneficial to their day to day life. A good number of stakeholders strongly agreed that the provision of solar PV brought quality education, prospects of jobs, better communication and increased community meetings. Besides, the Health personnel seems to have agreed that apart from extended health hours and increased immunization amongst children, the solar PV brought a number of benefits to the community. Moreover, teachers noted that the solar PV for lighting in the evening extended teachers' class preparation.

BENEFITS	GROUPS' RESPONSE TO CONTRIBUTION OF CRED PROJECT					
	HSA	TBA	E. COMM	TEACHERS	WOMEN	STUDENTS
Increased students study time (improved grades/job prospects) better studying environment)	■	■	■	■	■	■
Savings on phone charging	■		■	■		
Time saving i.e. close location for charging phones	■			■		■
Contributes to community fund	■					
Increased community group meetings	■		■	■	■	
Income generation from sale of cold drinks	■		■			
Household energy savings			■		■	■
Less competition for communal energy sources at household level						■
Extended teachers' class preparation in the evening				■		
Reduction in respiratory health problems	■					
Increased availability of immunization vaccines	■		■			
Extended emergency health hours	■				■	
Improved working environment for health workers and better health care provision	■	■	■			

■ Means contribution

Meanings: TBA – Traditional Birthing Assistant, HAS – Health Service Advisor

Table 4. 5: Stakeholders Perceived Benefits of the Solar Installations by CRED Project. Source Picken (2010)

4.1.1.2 Discussion and Conclusion of Social Sustainability

The social and economic significance of solar power is much appreciated in the remote rural areas than where national grid electricity already exists. CRED sites in the remote rural southern region of Malawi in Chikhwawa and Chiradzulu districts are living testimony as the discussions in the previous sections demonstrates. Of course, a twelve months experience is not enough to draw firm conclusions on social and economic impact of any developmental work. However, there are early indications useful lessons that have been learnt during this short spell of time in all CRED sites.

Correspondingly, in the context of financial sustainability, the project has demonstrated significant income generating activities that have been observed running steadily and enthusiastically for a longer time compared to the pre-solar PV period. It has been observed that the funds collected from the use of the solar PV system are put in a central fund account and the energy committee manages the fund on behalf of the local community. So far results at Malavi show a promising trend of income generation that can achieve battery replacement, however accounting and transparency need to be improved. It was established that at Malavi, the Head Teacher assumed the roles of secretary and treasurer besides the energy committee having elected positions of treasurer and secretary. This caused a lot of conflict amongst the CRED members because they were not getting accurate reports from the Head Teacher about how fees collected from the use of the solar PV system were being spent. Therefore, it is argued that if there can be increased communication amongst members about how fees are collected and spent and also if all the people can develop a more participatory decision making process then this will improve transparency and accountability on how fees are managed.

Also, results at Mwanayaya suggest good prospects for income generation levels, banking has been successful, however, accountability and transparency of funds still remains a major challenge and could be improved as already mentioned above. Namira and Mwalija have had less promising results via their cold drinks sales and this demonstrates the importance of phone and battery charging as the most powerful methods of income generation. Although it can be acknowledged that income generation is significant, Picken (2010), who evaluated the social impacts of the CRED project, highlights that this is also the area for the greatest potential for conflict. There are divergent views currently held amongst some energy committee and their local community regarding the use of funds generated through the solar income generating activities and also a feeling of lack of decision making equality and participation regarding what should be done with the profits. Therefore to make good use of this communal energy resource and in order to reduce the conflicts amongst local people, the relationship of cooperation with the target local people and energy committee must be further built up and developed.

Similarly, the social and institutional sustainability has been enhanced. The energy committee has worked to sensitize the local community that the solar PV is seen as communal resource and has enhanced acceptability of the solar PV technology. Various groups have been utilizing the solar PV, as shown in Table 4.5, in the evening to discuss activities that affect their lives thereby enhancing equity participation by stakeholders. Additionally, the project has trained consumers in system use, safety and maintenance. However, there is need for re- training because some responsible people within the energy committee may move away. This will be necessary in order to prepare for when new people move to the village, as well as re-training for the maintenance staff / responsible persons, as some of them might move away from the village. In addition to the regular training for maintenance staff and end-users, the original training sessions need to also include plans for updated re-training and continued training of the local users.

In creating ownership of the solar PV system, regular meetings were held by the village authorities, the actual formalities and project procedures were discussed. The energy committee that is comprised of 10 people (Figure 4.4) was formed to increase the local people's participation and responsibility. This enabled the local people to participate and input their ideas, formulate their expectations and apply their expertise right from the start. Apart from that it sensitized and promoted the local community to use the system to their benefit in a controlled manner (Appendix 8). However, the major challenge has been to strengthen further the sense of ownership of the community based approach energy resource. An evaluation CRED project report for 2010 at Mwanayaya School and Health centre Picken (2010) echoes that while the energy committee perform practical functions in a competent manner, they struggle to reach strong levels of ownership and decision making with regards to the CRED project activities.

Members of the community out with the energy committee have low levels of participation or ownership. This threatens the project to attain sustainability.

Another central factor to solar PV system sustainability is the training of technicians/ local staff to enhance sustainable operation and maintenance of the solar PV system (Appendix 6). This results into the enrichment of local expert knowledge on solar PV operation and maintenance. The CRED Energy Committee was trained on maintenance and operation, and look after the solar PV system. This has resulted in more local knowledge on energy issues. Furthermore, the CRED model was designed to take into account sustained operation and maintenance as being a crucial precondition for enabling sustained good quality of life amongst the remote rural population. Also as part of maintenance plan of solar PV systems, the CRED project has embarked on solar PV system performance monitoring to enhance system sustainability. The performance monitoring instruments have been mounted at Mikolongo and Malavi Cred sites. The data is collected on monthly basis for performance system analysis and include state of charge, battery voltage, charging and discharging currents, module current and solar insolation. Currently, the analyzed data assists in the preventive maintenance of the system.

A review of factors that lead to low sustainability of solar PV systems in Sub Saharan Africa was provide in section 2.1.4, and many authors recognize theft and vandalism as one of the major problems. It has been observed that ever since installations were done in 2008, theft and vandalism has not been a serious problem in the CRED sites. This could largely be attributed to the fact that CRED project implemented a number of security measures such as (i) all the systems are installed in the premises of the schools and health centres and panels are installed on the roof tops, and that there is a close social control over them (ii) burglar bars on classroom windows and doors, and security enclosures on battery banks and inverter (iii) a night watchman or members of the energy committee on duty rota per night to take responsibility of the security of the equipment.

4.2 Technical Results

4.2.1 Technical Sustainability

This section gives results for outdoor performance of the panel technology (Mono-crystalline solar cell) used in the CRED project solar PV installations and it also gives assessment of the performance of some of the solar PV components used in the CRED project. It starts by looking at the geographical position of the study area and outlining the technical description and system components of the solar PV system installed at the CRED sites. Subsequently, the technical results are discussed and conclusion is drawn.

4.2.1.1 The Study Area

The study areas are districts of Chiradzulu and Chikhwawa in southern part of Malawi. The Community Rural Electrification and Development (CRED) centres comprise mainly schools and health posts. The two locations are at different altitude, Chikhwawa at 94 metres and Chiradzulu at 1109 metres above sea level. The difference in altitude of the two locations facilitates direct comparison of the performance of the solar PV systems. To date, there are seven installations of solar PV in the CRED centres located in the remote areas. The main characteristics of solar PV system in these centres include a module, a battery bank, charge controller, a DC/AC inverter and the load (appliances). The experimental layout (Figure 4.14) and a summary of data acquisition equipment (Table 4.10) are as shown.

4.2.1.2 Technical Description of Solar PV at CRED Sites

(Malavi School in Chiradzulu District and Mikolongo School in Chikhwawa District)

Characteristics:

- PV Array – 2x 75W panels
- Charge Control – Steca 12Amps
- Batteries – 2x 102Ah Deltec
- Inverter – 600W TES feeding 1 socket
- 18x 11W DC bulbs – 2 rooms each with 8 then 2 security lights

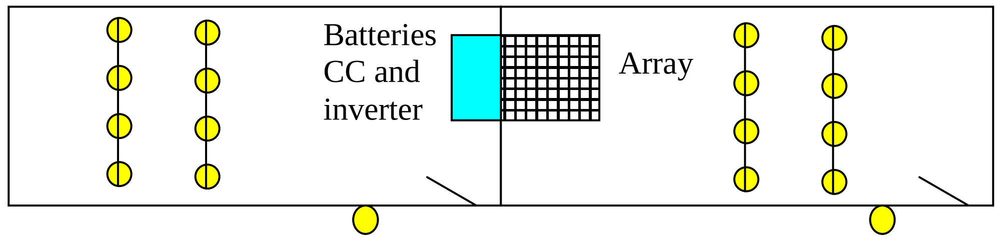

Figure 4. 7: System 1 – Typical Design Layout for Lighting in a Standard Classroom School Block. Source: CRED (2009)

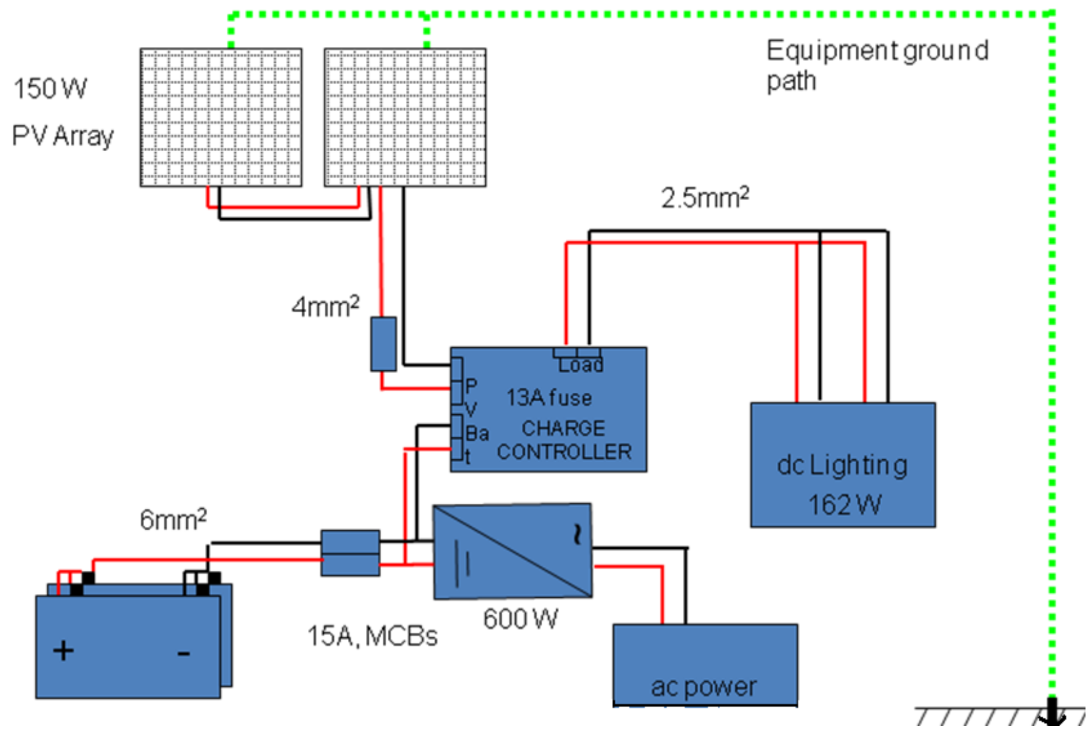

Figure 4. 8: System 2 – Typical Wiring Diagram for Lighting and Power for a Standard Classroom School Block. Source CRED (2009)

Characteristics:

- PV Array – 2x 75W panels
- Charge Control – Steca 12Amps
- 8 x 50Ah batteries in teachers' houses. System will charge 2 at a time from a maximum of 50% discharge.

4.2.1.3 System Components of Solar PV

(a) PV Array

This consists of two 75 Wp Mono-crystalline modules giving a total rated installed capacity of 150 Wp per site (Figure 18). The Mono-crystalline modules have 32 cells connected in series with a physical specification of 527 x 1037 x 35 mm. The modules have been mounted on mounting racks at optimal inclination approximately equal to the latitude to provide maximum annual yield for each respective location (Figure 4.10). Detailed specification of the Monocrystalline solar cell installed at the CRED sites is shown in Table 4.7 & Figure 4.9 below:

Manufacturer	Module Type	Technology	Module Specifications
LORENTZ	LA75 – 12S	Monocrystalline	• Peak power = 75 Watts Tolerance % = +15/-5 • Max. Power current = 4.6 Amps • Max. Power voltage = 16.5 Volts • Short circuit current = 5.4 Amps • Open circuit voltage = 21.0 Volts • Efficiency of cells = 17.0 % • Temperature coefficient of Pmax = -0.38%/^{0}C • Temperature coefficient of V_{oc} = -60.8mV/^{0}C • Temperature coefficient of I_{sc}= 3.0 mA/^{0}C • Max. System voltage = 600 V • No. of cells and connection = 32 in series

Table 4. 6: Specification of Mono-Crystalline Solar Cell Installed at the Study Area (All technical data at standard test condition: Air Mass = 1.5, E = 1,000 W/m^2, Cell temperature = 25 ^{0}C)

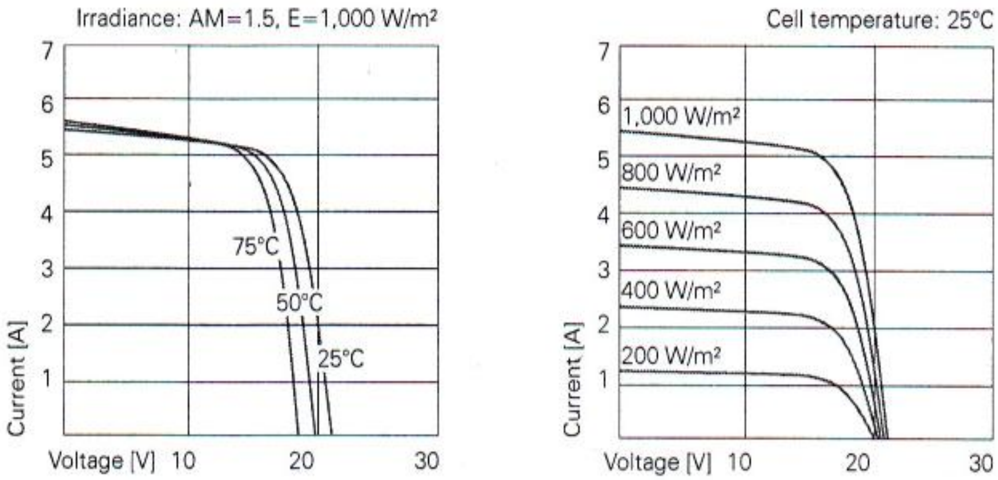

Figure 4. 9: The Current – Voltage Curve of Mono Crystalline Solar Cells. Source: Lorentz Solar Cell Manual and www.lorentz.de

Figure 4. 10: Outdoor Solar PV Monitoring System Showing Mono-crystalline PV Modules and Radiation Sensor. Source: Authors own experimental set up and camera pictures

(b) Charge Controller

The charge controller (Figure 4.11) has been installed between the PV array and the batteries to regulate the power supply from the power source and to protect the batteries from too low discharge. The charge controller specifications are given in (Table 4.7) and is designed and manufactured by Steca Tarom. The charge controller of this type have been designed to cut off the PV array when the battery is fully charged at 13.7 V and disconnects the load when the battery reaches its low voltage cut out of 11.8 V (Table 4.7). It has outlets for solar module, battery and load. In addition, the charge controller has an external port for data logger connection. The intelligent System Manger, in which a microprocessor has been employed, performs the duty of regulating, controlling and monitoring functions. A typical data from a clear summer day from the charge controller used in this project is as shown in Appendix 2.

System Parameter	**Value**
Voltage	12 V
Nominal Module current at 20^0C	35 A
Nominal Load current at 20^0C	35 A
Maximum current for 10 seconds	45 A
Maximum pulse current	140 A
Temperature range during operation	-10^0C to 80^0C
High disconnection voltage	13.7 V
Low disconnection voltage	11.8 V

Table 4. 7: Charge Controller System Parameters

Figure 4. 11: Steca Tarom Data Logger and Charge Controller

(c) Battery Bank

The system has an installed battery capacity of 12V x 204Ah and is a 12V DC system. The battery bank consists of 2 x 12V Deltec Lead Acid deep cycle batteries and each with 102 Ah capacity (Figure 4.12). The two batteries are connected in parallel giving a total battery bank capacity of 2.448 kWh and have been designed to account for 2 days of autonomy. The battery bank life expectancy if used and maintained properly is more than 5 years for this type of battery. The instructions for use are as follows: a minimum battery bank voltage of 11.8 V, a maximum battery bank voltage of 13.8 V and a maximum Depth of Discharge of 20% after 2 days of no sunshine. This translates to an average maximum Depth of Discharge of 10% per day and for 2 days without sunshine or cloudy conditions it translates to 20%. Additionally, the battery bank is enclosed in a wooden box and is well ventilated to keep the temperature at ideal room temperature of 25 ^{0}C. The battery specifications are given in Table 4.8 below:

Manufacturer	Deltec High Recycle
Battery capacity at 20 hr rate	102 Ah
Battery bank installed capacity	204
Installed Voltage	12
Number of Batteries	2
Load Test	310A

Table 4. 8: Battery Bank Specifications

Figure 4. 12: Battery bank, Charge Controller and Inverter

(d) Solar PV System Load

The system load comprises of the following (Figure 4.7):

- 18 x 9W DC energy saving bulbs
- Assuming:
- 2 days of autonomy
- 3 hours/day of lighting
- 3 hours/day of laptop use
- 2 hours/day of mobile phone charging

4.2.1.4 Description of Monitoring Instruments

(a) SDL-1 Solar Data Logger

The radiation sensor of Model SDL -1 (Figure 4.13) is a self contained energy meter that measures the sun's irradiance at regular intervals for up to 170 days at a time. The radiation sensor has a photodiode that has a spectral sensitivity from 400nm to 1100nm and overlaps the solar radiation spectrum from about 300nm to 1800nm. The short circuit current of the photodiode is directly proportional to the intensity of the radiation. It is powered by a standard 9V alkaline battery and has a typical battery life of more than 2 years. It has also a USB interface that allows data to be downloaded to a computer for analysis. The communications programme Hyper Terminal (Standard on Windows based computers) or any serial capture can be used to capture logged data to a text file. The data can then be analyzed and plotted using a spreadsheet programme as shown in Appendix 3

Figure 4. 13: SDL-1 Solar Data Logger

The CRED solar PV systems have been monitored for more than ten months starting from mid September of 2010. The measured quantities include meteorological parameters such as the sun's irradiance, ambient and module temperature and electrical quantities include measurement of state of charge, module and battery current, total current and battery voltage obtained at each module output (Figure 4.14, Appendix 5).

(b) Steca Tarom Data Logger

This type of data logger is designed to easily interface with the Steca Tarom charge controllers. It stores up to 8,176 data sets with all the system parameters as voltage, currents, state of charge and system status. The logger has an analog input which can be used to trace the radiation data. Additionally, the modem version of the logger allows remote monitoring of the solar system. Once the data logger is connected to the Tarom regulator, it starts to collect data. The Tarom sends each minute the actual system values to the logger. Depending on the logging frequency all values collected during one period are used to calculate the average which will be stored. If they occur at least once during the collection period they will stay until the end of this period. If all the data sets are completely used, the TarCom logger overwrites the oldest data again. This process ensures that the newest data of actual logging period is available. The data logging system acquires and stores data at set intervals. The Tarom data parameters are as shown in Table 4.9.

System Parameter	**Value/Range**
Voltages Via Tarom Regulator	12, 24, 48 V
Battery voltage	8 to 65.5 V
Logging interval	2, 4, 8, 16.....256 min
Memory size	8176 data sets
Own consumption	5mA (ETN: 60mA)
Sensor input range	0 to 150mV
Maximum current alarm relays	50mA, 50V
Ambient temperature	-20^0C to 50^0C

Table 4. 9: Steca Tarom Data Logger Parameters

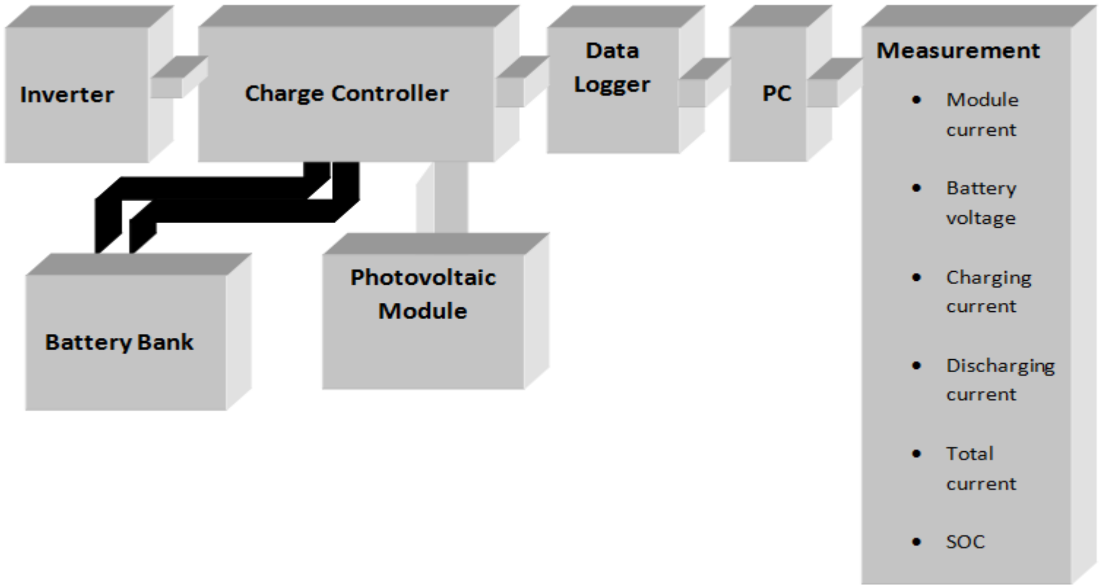

Figure 4. 14: Layout of Experimental System

Parameter	**Transducer**	**Manufacturer**	**Model**
State of Charge Battery voltage Charging currents Discharging currents	Steca Tarom Solar Charge Controller	Steca Electronics	Tarom 235
Ambient temperature	Steca Tarom Solar Charge Controller	Steca Electronics	Tarom 235
Irradiance Cumulative Solar energy	Solar Data Logger	Micro Circuit Labs	SDL – 1
Data storage	Steca PA Tarom Data Logger	Steca Electronics	TarCom01

Table 4. 10: Installed data acquisition equipment and sensors at both test sites

4.2.2 Results and Discussion of Technical Sustainability

This section examines the components of the solar PV used in the CRED project and it assesses how the components performed for a period of ten months. The system has been monitored by the measuring instruments discussed above and the parameters collected from the solar PV system are outlined. Representative days in summer and winter which represent seasonal variations and have been used to assess the performance of the system components which are an important consideration in solar PV systems where the output of the PV component is far more critical and could mean the difference between being able to meet a load and experiencing an energy shortfall.

4.2.2.1 Technical Performance Data Collection

The following signals were continuously monitored in order to analyze the system performance and demonstrate technical sustainability of the CRED Community Based Solar PV system.

- The current from the solar panel to the charge controller. This is the input current and designated as the module current (I_{mod})
- Voltage across the battery's terminals (U)
- The charging and discharging currents to and from the battery designated as I_{in} and I_{out} respectively
- The total current (I_{total}) being the resultant current between charging and discharging currents
- The state of charge of the battery (SOC)

-The ampere Hours of the battery (AH)

-The ampere Hours/Day (AH/d)

-The efficiency of the module and load

Table 4.11 shows an overview of average monthly system parameters for a period of ten months when the system was operational at Mikolongo CRED site. All collected data from the logger is displayed in Table 4.11. These data sets were stored to a file exported to an excel sheet or visualized in a chart form (e.g. as shown in Figure 4.16). It important to note that the average displayed data sets was captured over a period of one month. The data sets include the module current, battery voltage, system energy use and state of charge the battery. From Table 4.11, it can be observed that the solar insolation, battery voltage and module current have decreasing values from October to June and start rising in value after the month of June. It is clear that the characteristics of these data sets followed seasonal pattern, that is to say, being higher in dry season and falling towards winter when the insolation in Malawi decreases.

However, the insolation data shown in Table 4.11 was captured separately using SDL 1- Data Logger shown in Figure 4.13 which has self contained energy meter that measured the sun's irradiance at 15 minutes intervals. It has been observed that the solar insolation decreased from the month of October until June and started rising again in the month of July. The decrease in insolation can be attributed to the seasonal variability of global horizontal insolation. It has been noted that the summer months of October and November exhibit the greatest average monthly insolation, due to longer days, more direct exposure to the sun due to the tilt of the Earth's axis, and to generally clearer skies. In addition, it can be said that local weather conditions have a significant effect on seasonal and short-term solar radiation. Table 4.11 for Mikolongo site shows that there is a sharp drop in insolation from December until late summer months of March and April when the rainy season occurs in Malawi. On one hand, in the winter months of May to July, the days are shorter, cloud cover is greater, and the sun is lower in the sky, requiring sunlight to travel a longer path through the atmosphere and be scattered by clouds, dust, and pollution before reaching the Earth's surface. Therefore, insolation is lowest in the winter period as depicted in Table 4.11.

Month	State of	Tarom Reading	Solar Insolation	Panel Area	Panel Generated	Max. Power Point	Panel Generated	Module Efficiency	System Energy Use (%)		
	Charge (%)	kAh (Ψ)	KWh/m2 (λ)	m2 (ρ)	kWh (μ)	Voltage (φ)	kAh ε= (μ/φ)	(Ψ/ε)*100%	Battery	Load	Un Used
October	96	1.83	174.78	1.09	191.03	13.40	14.26	12.84	49.00	4.00	47.00
November	91	1.77	170.35	1.09	186.19	13.45	13.84	12.79	81.00	4.00	15.00
December	96	1.57	154.05	1.09	168.38	13.40	12.57	12.47	55.00	4.00	41.00
January	96	1.42	145.03	1.09	158.52	13.30	11.92	11.91	36.00	3.00	61.00
February	94	1.34	135.22	1.09	147.80	13.20	11.20	11.98	57.00	4.00	39.00
March	94	1.23	127.45	1.09	139.30	13.35	10.43	11.79	50.00	3.00	47.00
April	94	1.18	126.92	1.09	138.72	13.40	10.35	11.40	50.00	3.00	47.00
May	93	1.12	119.39	1.09	130.49	13.30	9.81	11.42	50.00	3.00	47.00
June	95	1.01	118.00	1.09	128.97	13.45	9.59	10.54	45.00	2.00	53.00
July	96	1.23	120.00	1.09	131.16	13.45	9.75	12.61	51.00	4.00	45.00
						Average System Energy Use in %			52.40	3.40	44.20

Table 4. 11: Summary of System Performance – Mikolongo

Similarly, Table 4.12 shows an overview of average monthly system parameters for a period of ten months when the system was operational at Malavi CRED site. All collected data from the logger is displayed in Table 4.12. These data sets were stored to a file exported to an excel sheet or visualized in a chart form (e.g. as shown in Figure 4.16). It important to note that the average displayed data sets was captured over a period of one month. The data sets include the module current, battery voltage, system energy use and state of charge the battery. From Table 4.12, it can be observed that the solar insolation, battery voltage and module current have decreasing values from October to June and start rising in value after the month of June. It is clear that the characteristics of these data sets followed seasonal pattern, that is to say, being higher in dry season and falling towards winter when the insolation in Malawi decreases.

However, the insolation data shown in Table 4.12 was captured separately using SDL 1- Data Logger shown in Figure 4.13 which has self contained energy meter that measured the sun's irradiance at 15 minutes intervals. It has been observed that the solar insolation decreased from the month of October until June and started rising again in the month of July. The decrease in insolation can be attributed to the seasonal variability of global horizontal insolation. It has been noted that the summer months of October and November exhibit the greatest average monthly insolation, due to longer days, more direct exposure to the sun due to the tilt of the Earth's axis, and to generally clearer skies. In addition, it can be said that local weather conditions have a significant effect on seasonal and short-term solar radiation. Table 4.12 for Malavi CRED site shows that there is a sharp drop in insolation from December until late summer months of March and April when the rainy season occurs in Malawi. On one hand, in the winter months of May to July, the days are shorter, cloud cover is greater, and the sun is lower in the sky, requiring sunlight to travel a longer path through the atmosphere and be scattered by clouds, dust, and pollution before reaching the Earth's surface. Therefore, insolation is lowest in the winter period as depicted in Table 4.12.

Month	State of Charge (%)	Tarom Reading kAh (Ψ)	Solar Insolation KWh/m2 (λ)	Panel Area m2 (ρ)	Panel Generated kWh (μ)	Max. Power Point Voltage (φ)	Panel Generated kAh ε= (μ/φ)	Module Efficiency (Ψ/ε)*100%	System Energy Use (%) Battery	Load	Un Used
October	92	1.85	175.80	1.09	192.15	13.40	14.34	12.90	90.04	4.96	5.00
November	82	1.71	164.98	1.09	180.32	13.45	13.41	12.75	86.00	3.00	11.00
December	86	1.61	156.43	1.09	170.98	13.40	12.76	12.62	69.00	2.00	29.00
January	92	1.48	147.84	1.09	161.59	13.30	12.15	12.19	67.00	2.00	31.00
February	86	1.37	136.32	1.09	149.00	13.20	11.29	12.14	68.00	2.00	30.00
March	85	1.32	139.00	1.09	151.93	13.35	11.38	11.60	67.00	2.00	31.00
April	85	1.29	138.32	1.09	151.18	13.40	11.28	11.42	66.00	3.00	31.00
May	81	1.25	133.39	1.09	145.80	13.30	10.96	11.40	74.00	4.00	22.00
June	83	1.12	128.00	1.09	139.90	13.45	10.40	10.77	71.00	6.00	23.00
July	88	1.24	124.00	1.09	135.53	13.45	10.08	12.31	47.00	8.00	45.00
						Average System Energy Use in %			70.50	3.70	25.80

Table 4. 12: Summary of System Performance – Malavi

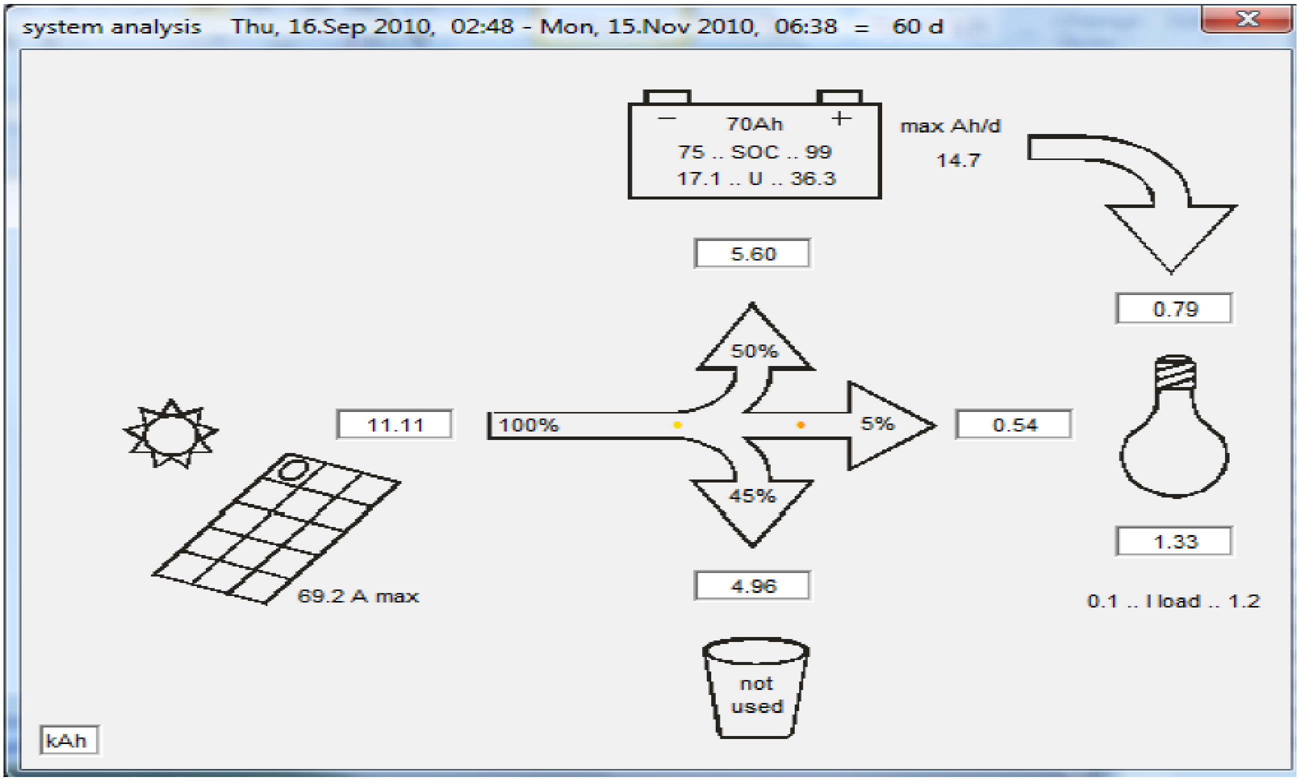

Figure 4. 15: Monthly System Analysis for Mikolongo Site

Figure 4.15 shows an example of how data was read out from the Tarom System Manager at Mikolongo CRED site. It is important to note that this is one of the Tarom System Manager drop down window that gives a quick but detailed overview of the solar PV system performance parameters and energy use; and is called the system analysis. Figure 4.15 has been included just to show how various quantities of the charge controller were captured. In this case, the data shown was captured starting from 16th September 2010 to 15th November 2010. From Figure 4.15, it can be seen that for the stated period the total generated energy from the module is 100%, the energy use for the battery bank, load and un used energy was 50%, 5% and 45% respectively. Also the range of state of charge of the battery and the battery voltage can be seen at glance. Moreover, the overall performance parameters can be analysed on daily, weekly and monthly basis by using the ‘day’, ‘week’ and ‘month’ keys

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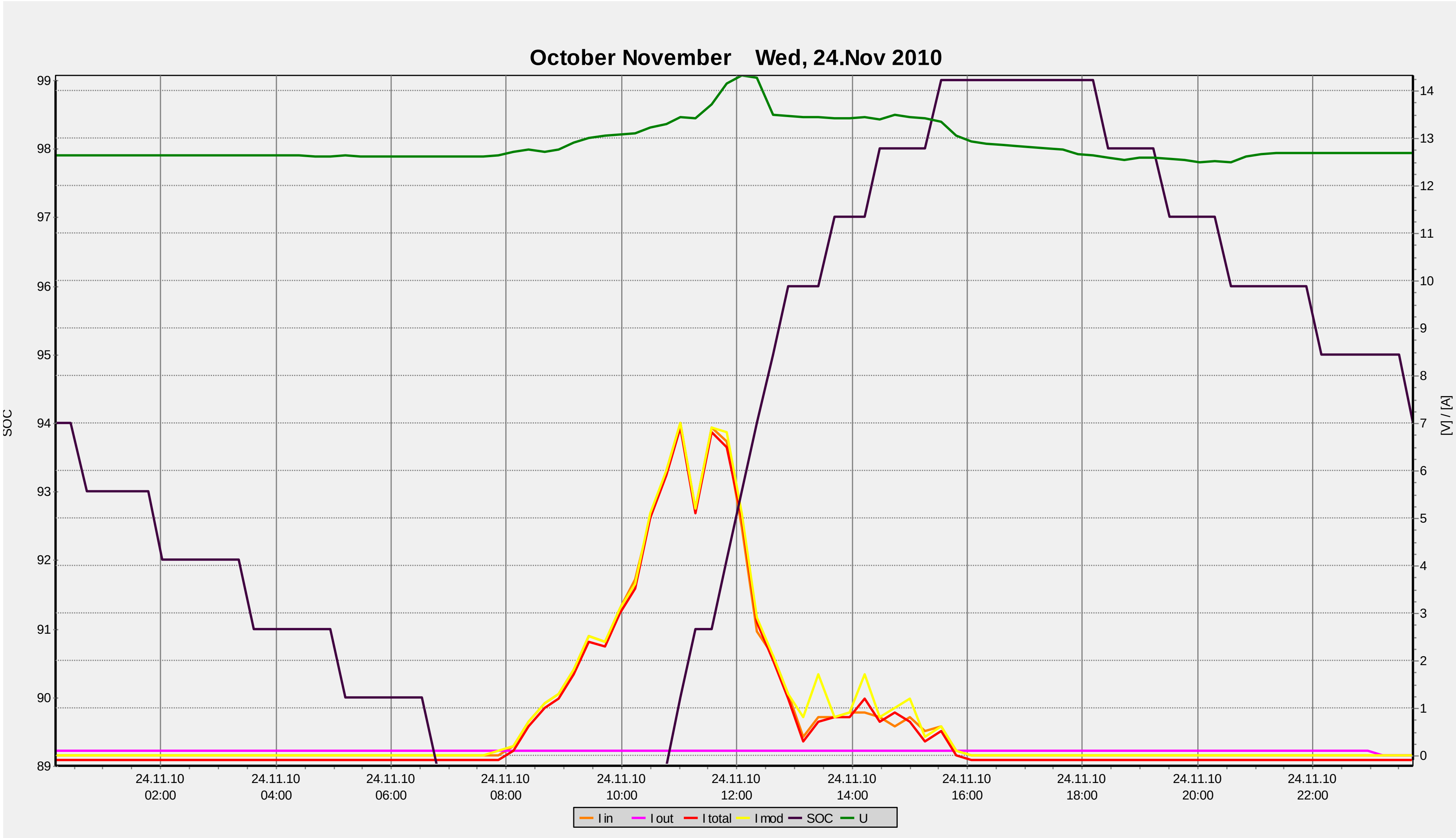


I in Charging Current I out Discharging Current I total Resultant Current from Charging and Discharging Currents SOC Battery State of Charge U Battery Voltage

Figure 4. 16: System performance on the 24th of October, 2010 – Typical Summer Day (Mikolongo)

In this section the performance of Mikolongo CRED solar PV system is discussed using a typical summer day. As it can be observed from Figure 4.16, the battery voltage (green curve) steadily remained constant from the previously day because of absence of insolation over the night. From 8 am until 12 noon, the battery bank voltage increased steadily with an increase in solar radiation and the battery bank voltage reached a maximum of 14.3V during this period. The battery bank voltage decreased between 12 noon and 1 pm. Since the power is a function of voltage and current, it can be deduced that when the battery voltage was reduced, the PV array power output fell too. However, the battery bank voltage remained fairly constant between 1pm until evening. The battery bank voltage did not vary greatly during the day but increased with increase in insolation in the morning (Figure 4.17) because of less usage of the system. The battery bank voltage remained constant in the evening once again because of absence of insolation. Similarly, the module current (yellow curve) remained constant between 6am and 8am. However, between 8am until 11am the module current increased with an increase in insolation until 12 noon. Thereafter, the module current dropped until 1pm. Also, between 1pm and 2pm, it is observed that there was variation of the module current and this can be attributed to the variation of the meteorological conditions during that time (cloudy conditions). Another point of interest is the state of charge (black curve) which shows a decrease from the previous day and continues dropping to its lowest value at 11am (89%). After 11am it starts rising again until it reaches 98% at 3pm. The period between 3pm and 6pm, the state of charge is constant. After 6pm, the state of charge starts falling once again. It was noted that the daily average solar insolation for the month of October was 4.1 kWh/m^2 and had a direct influence on the system performance.

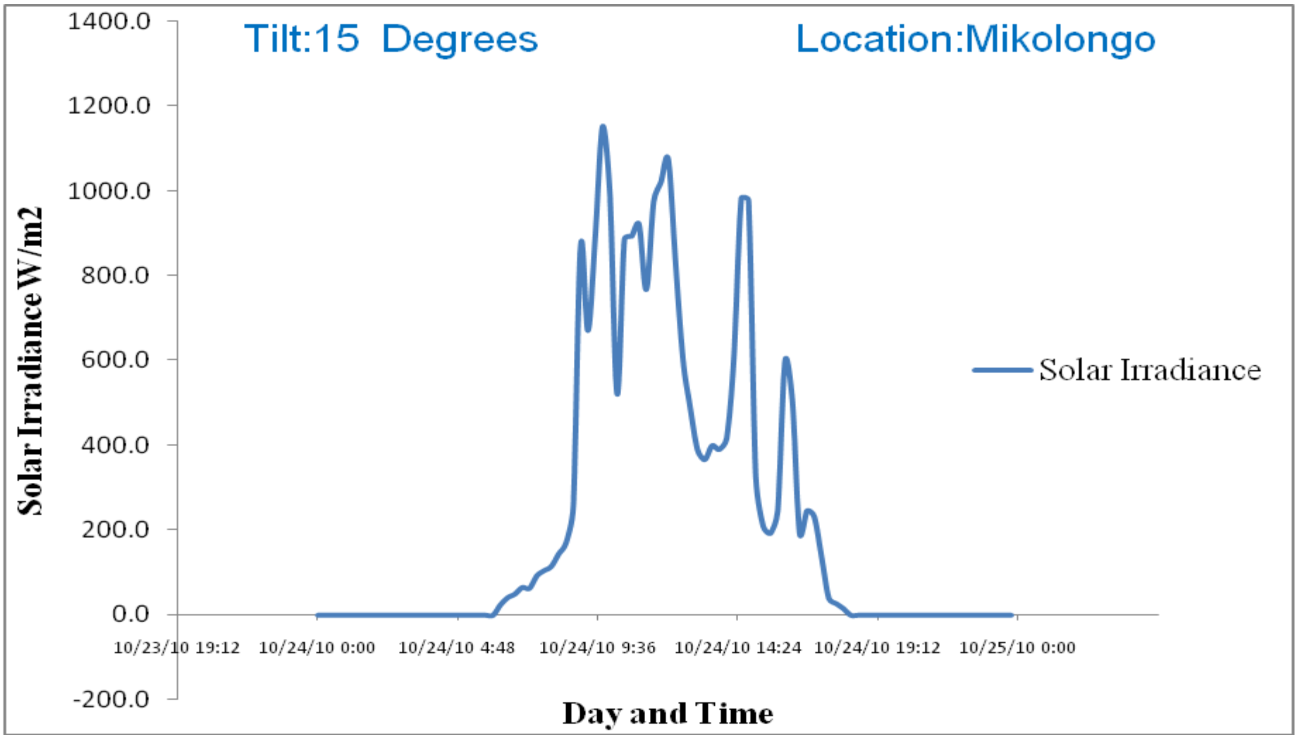
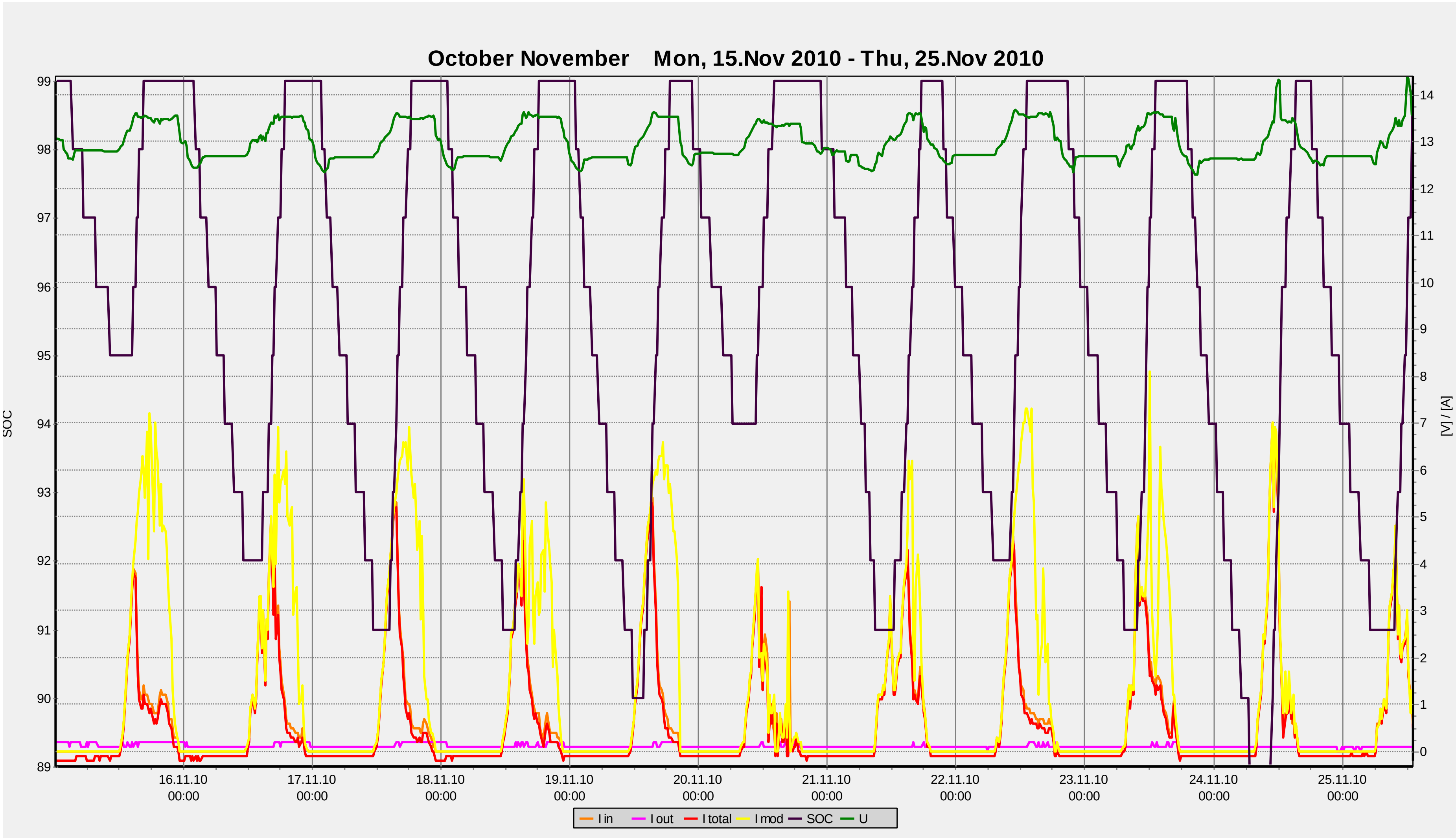


Figure 4. 17: Insolation on the 24th of October, 2010 – Typical Summer Day (Mikolongo)

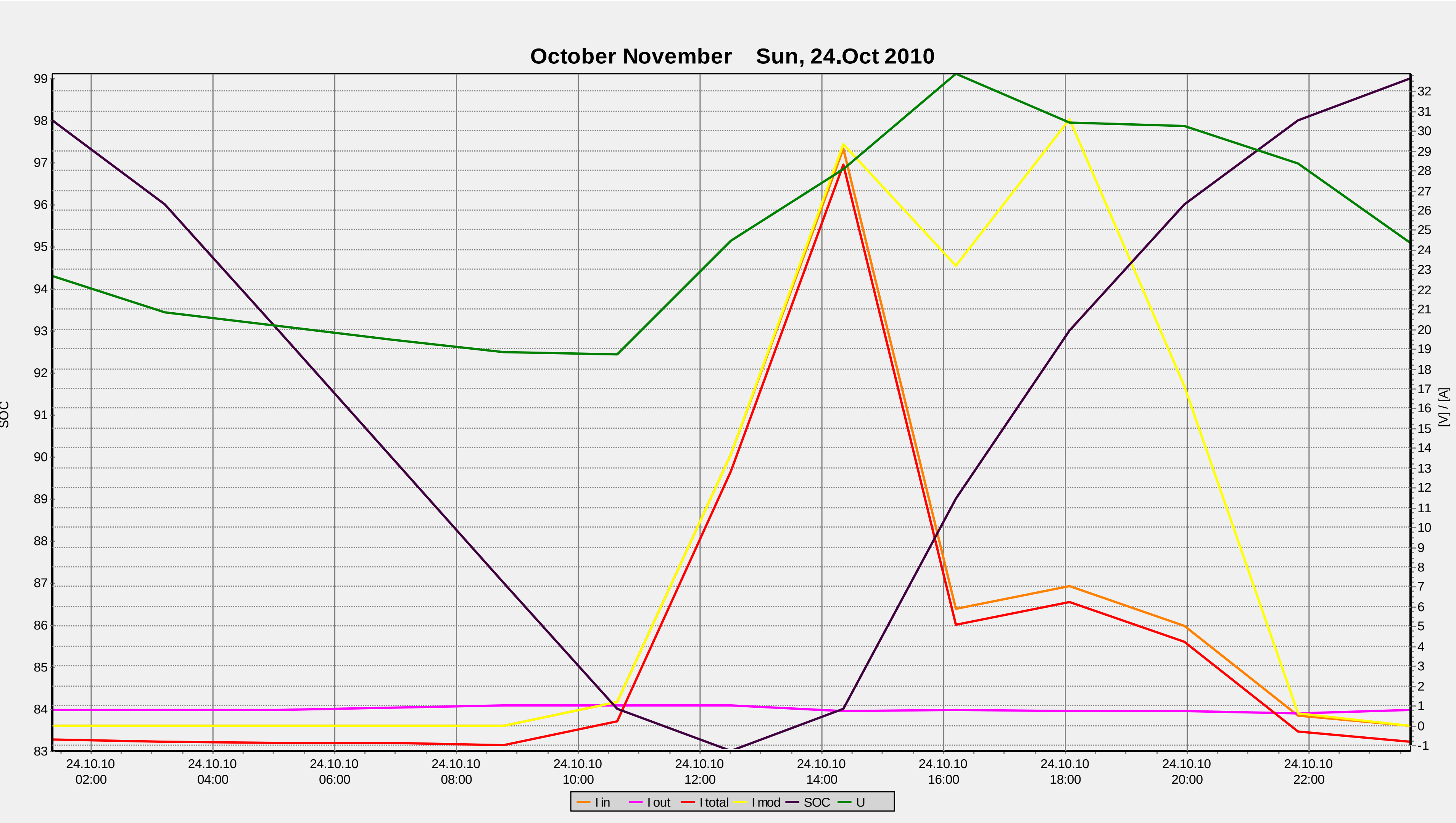
Similarly, in this section the insolation that had fallen at Mikolongo CRED site on a typical summer day is discussed. Figure 4.17 shows the variation of insolation in October at Mikolongo School. The curve is representing the global solar insolation and falling on a square meter surface area. The peak rate of incident solar energy occurred around noon and was greater than 900 Watts per square meter between 11am and 2pm. Over the full day, 4.78 kilowatt-hours of energy had fallen on every square meter of the surface as represented by the area under this curve. On this day, the sky was fairly unclear consequently the great variation of the curve with respect to meteorological conditions.



I in Charging Current I out Discharging Current I total Resultant Current from Charging and Discharging Currents SOC Battery State of Charge U Battery Voltage

Figure 4. 18: Performance of the system for 10 days (Summer Period -Mikolongo)

In this section the performance of CRED solar PV system at Mikolongo is discussed by observing the system performance over one week period. From Figure 4.18 it was observed that for a period of 10 days the battery voltage (green curve) in the summer month of October was always above 12.5 V. Also the battery bank was regularly at the full state of charge. There were no sustained periods of low state of charge of the battery bank. There were days when the battery voltage dropped but did not drop down below the safe operating value of 11.8V. Above that, there is evidence that the charge controller was operating normally. That is, despite having high charging current (red curve) of more 6A, the battery voltage dropped during that time



I In Charging Current I out Discharging Current I total Resultant Current from Charging and Discharging Currents SOC Battery State of Charge U Battery Voltage

Figure 4. 19: System performance on the 24th of October, 2010 – Typical Summer Day (Malavi)

In this section the performance of the CRED solar PV system at Malavi is discussed. As seen from Figure 4.19, the battery bank voltage (green curve) dropped considerably from the early hours of this day and remained constant between 8am and 10am. The solar irradiation (Figure 4.20) that overlapped the same period had risen steadily from 5am until it was the highest at around 10am. However, it is observed that the battery bank voltage was not the highest at that time but kept on rising until it was the highest at around 4pm. Another parameter of interest was the module current (charging current) which dropped sharply when the voltage was a maximum. This was an indication that the charge controller disconnected the battery bank from further charging. The battery bank voltage continued dropping considerably until 6pm. It has been assumed that considerable drop in battery bank voltage in the afternoon hours was due to load connection (phone charging and lighting) and the cloudy conditions on that day contributed to low charging current as well. It has been noted that lower radiation on that day, in the morning and evening, correspond with low battery voltage and explains the inability for the battery bank voltage to get back to its maximum state of charge after it was previous loaded. Also it has been noted that the daily average solar insolation for the month of October was 5.62 kWh/m^2 and had a direct influence on the system performance.

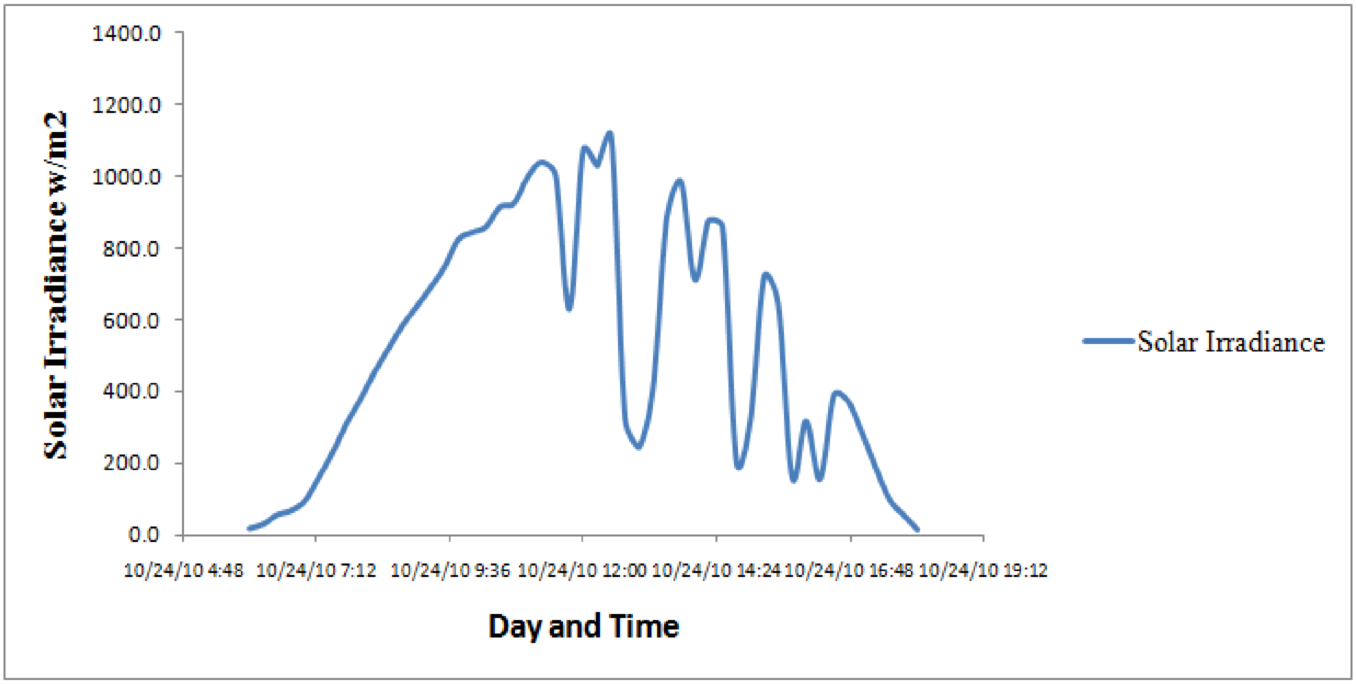
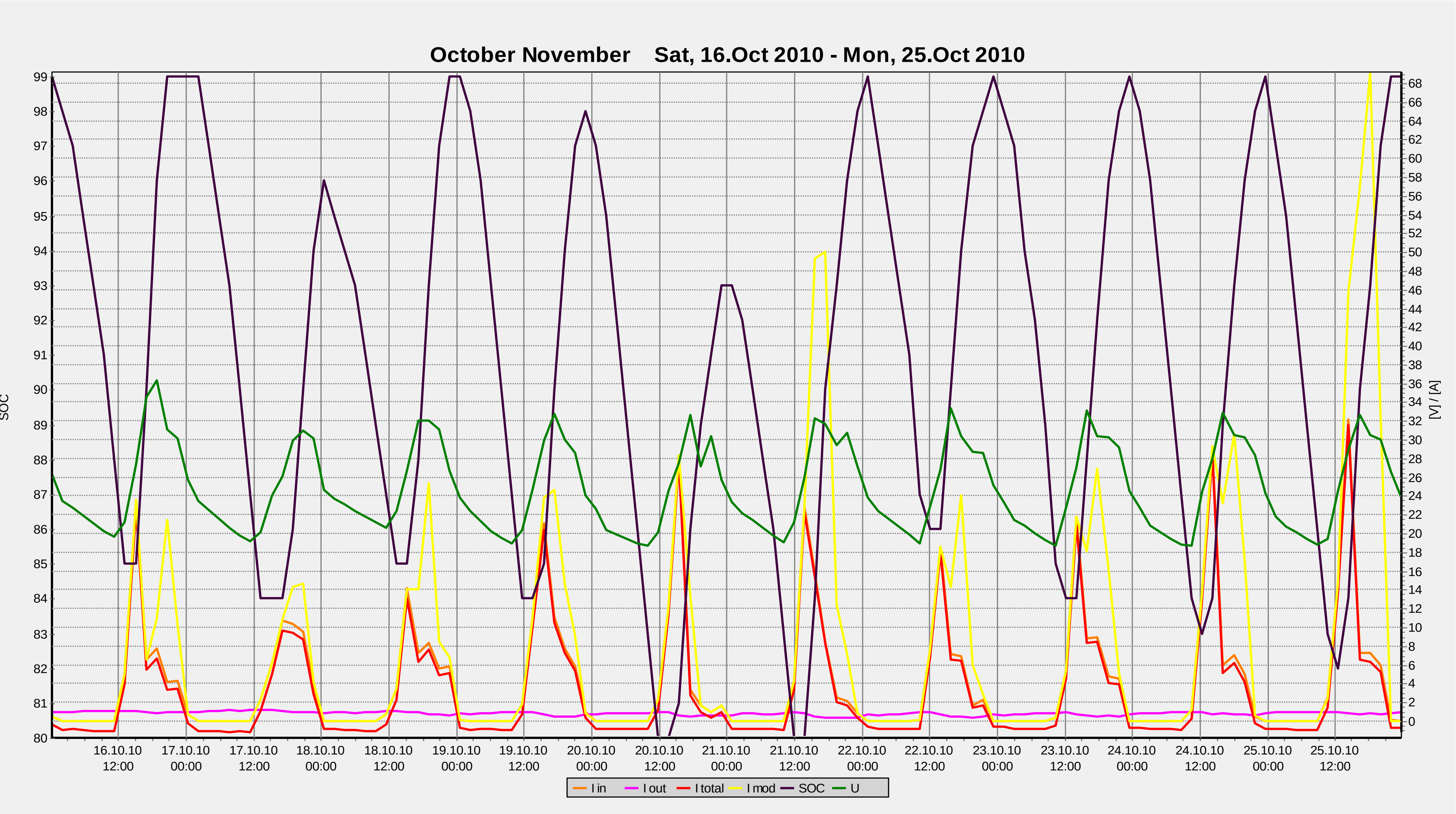


Figure 4. 20: Insolation on the 24th of October, 2010 – Typical Summer Day (Malavi)

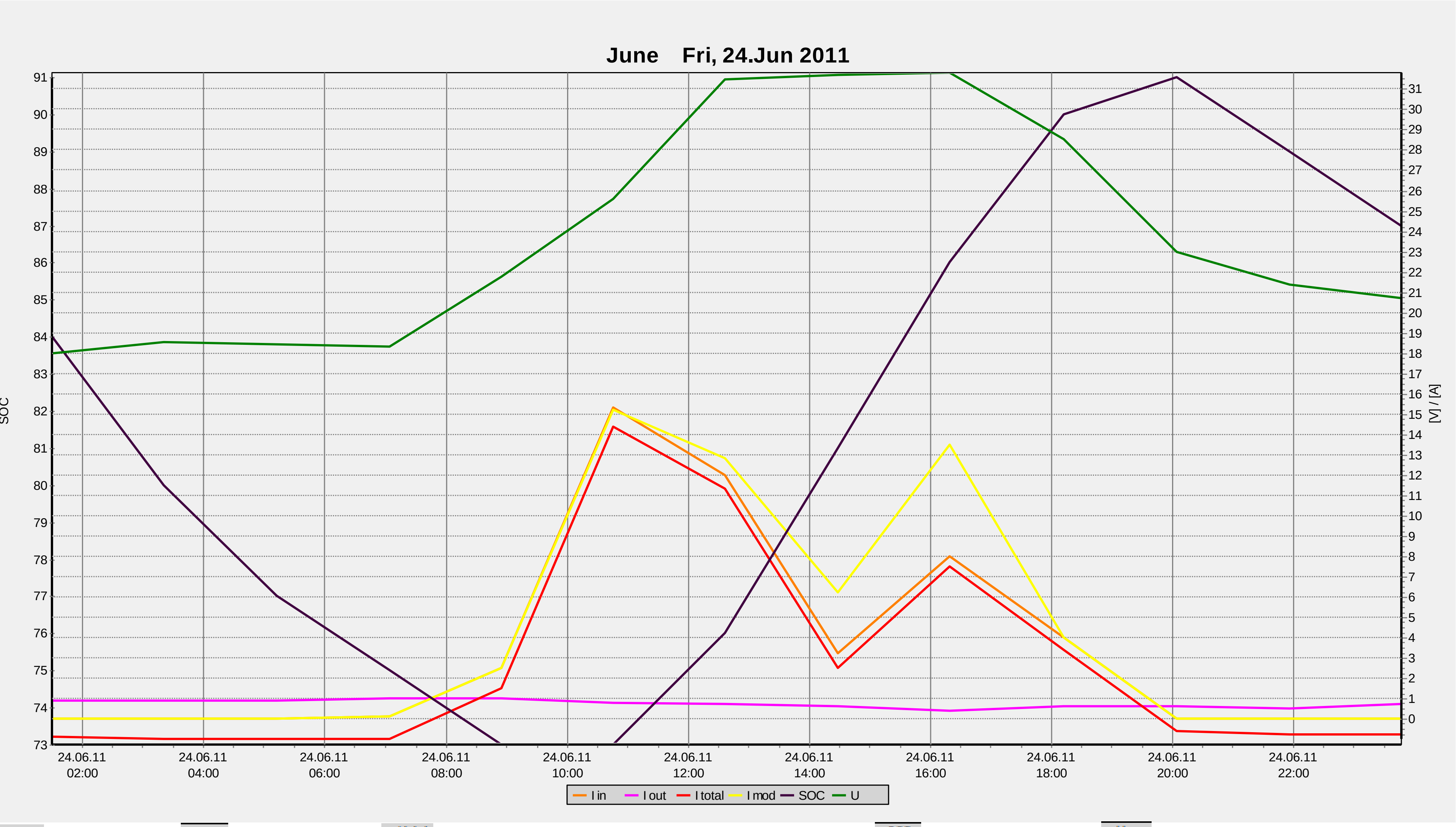
In this section the behavior of the insolation that had fallen on Malavi CRED site on a typical summer day is discussed. Figure 4.20 and Appendix 4 shows the variation of insolation in October at Malavi School. The curve is representing the global solar insolation and falling on a square meter surface area. The peak rate of incident solar energy occurred at 12:30am with 1111.6 Watts per square. However, between 11am and 12 noon the solar energy was well above 1,000 Watts per square meter. Over the full day, 6.35 kilowatt-hours of energy had fallen on every square meter of the surface as represented by the area under this curve. On this day, the sky was fairly unclear consequently the great variation of the curve with respect to meteorological conditions.



I in Charging Current I out Discharging Current I total Resultant Current from Charging and Discharging Currents SOC Battery State of Charge U Battery Voltage

Figure 4. 21: Performance of the system for 10 days (Summer Period –Malavi)

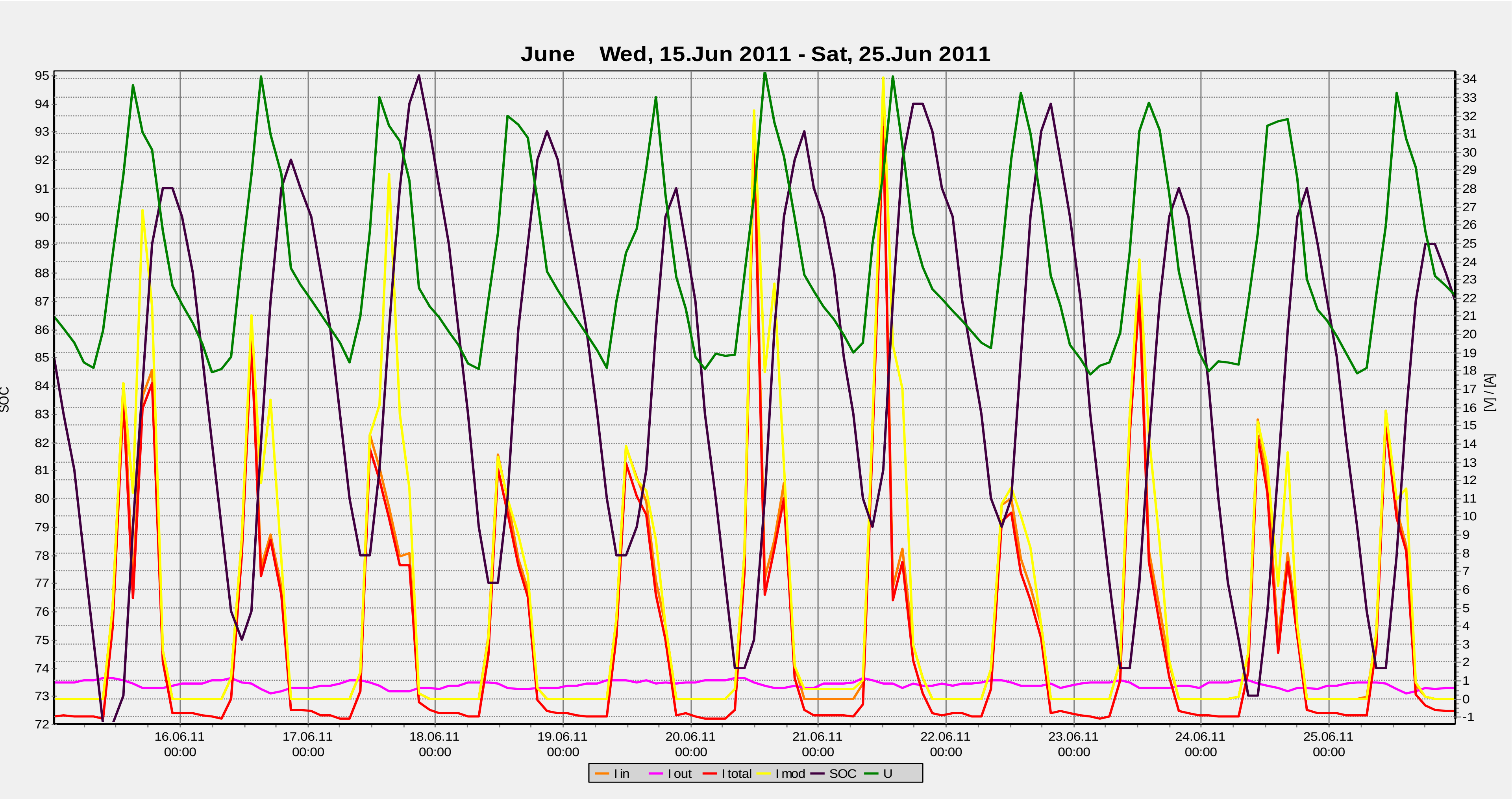
In this section the performance of CRED solar PV system at Malavi is discussed by observing the system performance over one week period. As it can be seen from Figure 4.21, high magnitude of module current (yellow curve) on 18th, 19th , 22nd and 29th days was observed. The high magnitude of module current did not affect the battery bank voltage. The battery bank voltage was maintaining a constant state on the lower and upper limit of safe charging and discharging cycles and was evidence enough to show that the the battery bank was properly regulated. It is also interesting to note that during this period there was more charge available going to the load. The battery state of charge did not change considerably during this period because the battery was fully charged both the previous day and the next logging day (Figure 4.19 & Figure 4.21). When the battery voltage reached the set point of the charge controller (13.7 V at 25°C) the current quickly dropped to an almost constant value going partly to the load and partly to the battery. The size of the current which goes to a nominally fully charged battery depends on the type and size of the battery and decreases very slowly with time because the battery is additionally charged at a very low rate.



I in Charging Current I out Discharging Current I total Resultant Current from Charging and Discharging Currents SOC Battery State of Charge U Battery Voltage

Figure 4. 22: System performance on the 24th of June, 2011 – Typical Winter Day at Mikolongo

In this section the performance of the solar PV system at Mikolongo CRED site on a typical winter day is discussed. As depicted from Figure 4.22, the module current (yellow curve) increased steadily between 9 am and 11 am. This matches with an increase in global solar radiation in the morning (Figure 4.22). During the same period, the battery bank voltage (green curve) remained fairly constant at 13.68V until 5 pm in the evening despite an increase in global solar radiation. It is also noted that the battery state of charge (black curve) increased steadily from 94% to 99% between 11am and 2pm and actually it remained fairly constant for almost the whole day. After 6pm the battery voltage decreased steadily to 12.92 V and it remained almost at the same value until the next day. The decrease in the battery bank voltage can be attributed to an increase in load in the evening when the system is being used most for community activities. The most interesting fact is that the battery bank voltage was kept between two safe operating limits of the charge controller for proper regulation of the battery bank voltage, that is, between 11.8V and 13.7 V for discharging and overcharging respectively. Another observation made is that the winter period has less sun hours and solar insolation in kWh/m^2 that summer period.



I in Charging Current I out Discharging Current I total Resultant Current from Charging and Discharging Currents SOC Battery State of Charge U Battery Voltage

Figure 4. 23: Performance for the system for 10 days (Winter Period – Mikolongo)

In this section the performance of the solar PV system at Mikolongo for a typical winter period over one week is discussed. Observation in Figure 4.23 shows that for a period of 10 days the battery voltage (green curve) in the winter month of June was regularly at the full state of charge. The battery bank voltage had a highest charging value of 13.8V and lowest discharge value of 12.4V for this 10 day winter period. There were no sustained periods of low state of charge of the battery bank. As the same case with the summer period, the system in the winter period did not register a voltage below the safe operating value of 11.8V. Above that, there is evidence that the charge controller was operating normally. The only clear difference is that the winter period has low values of module current (highest being 6.7A) and summer highest being 7.3A. That is, despite having high charging current of more than 6A, the battery voltage dropped during that time.

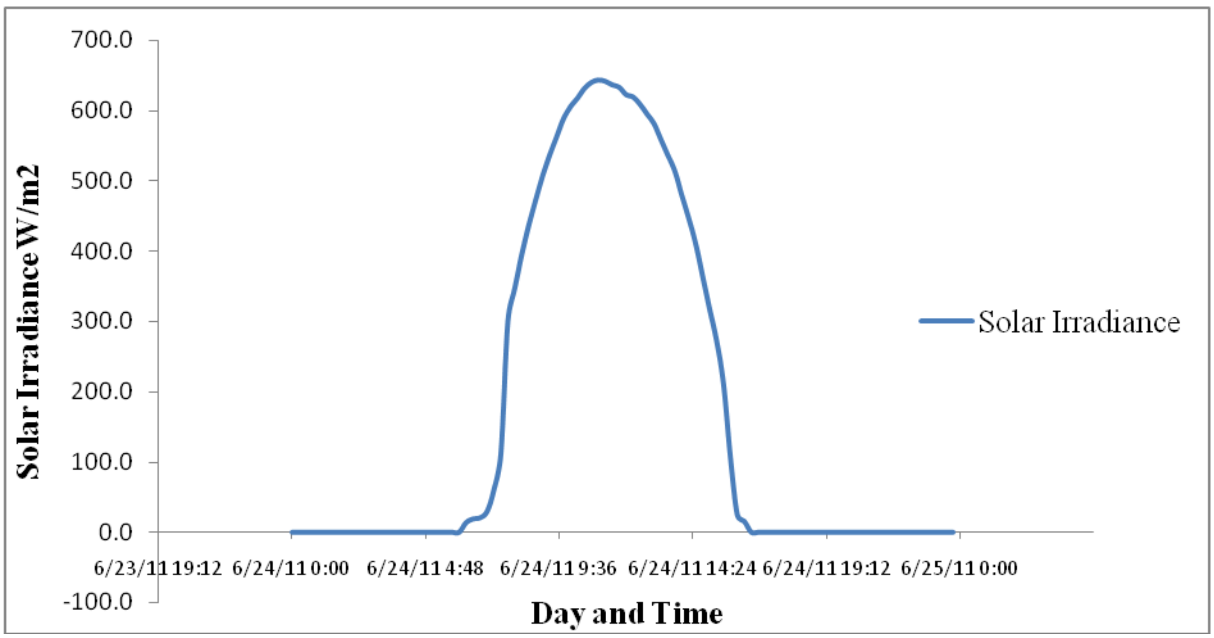
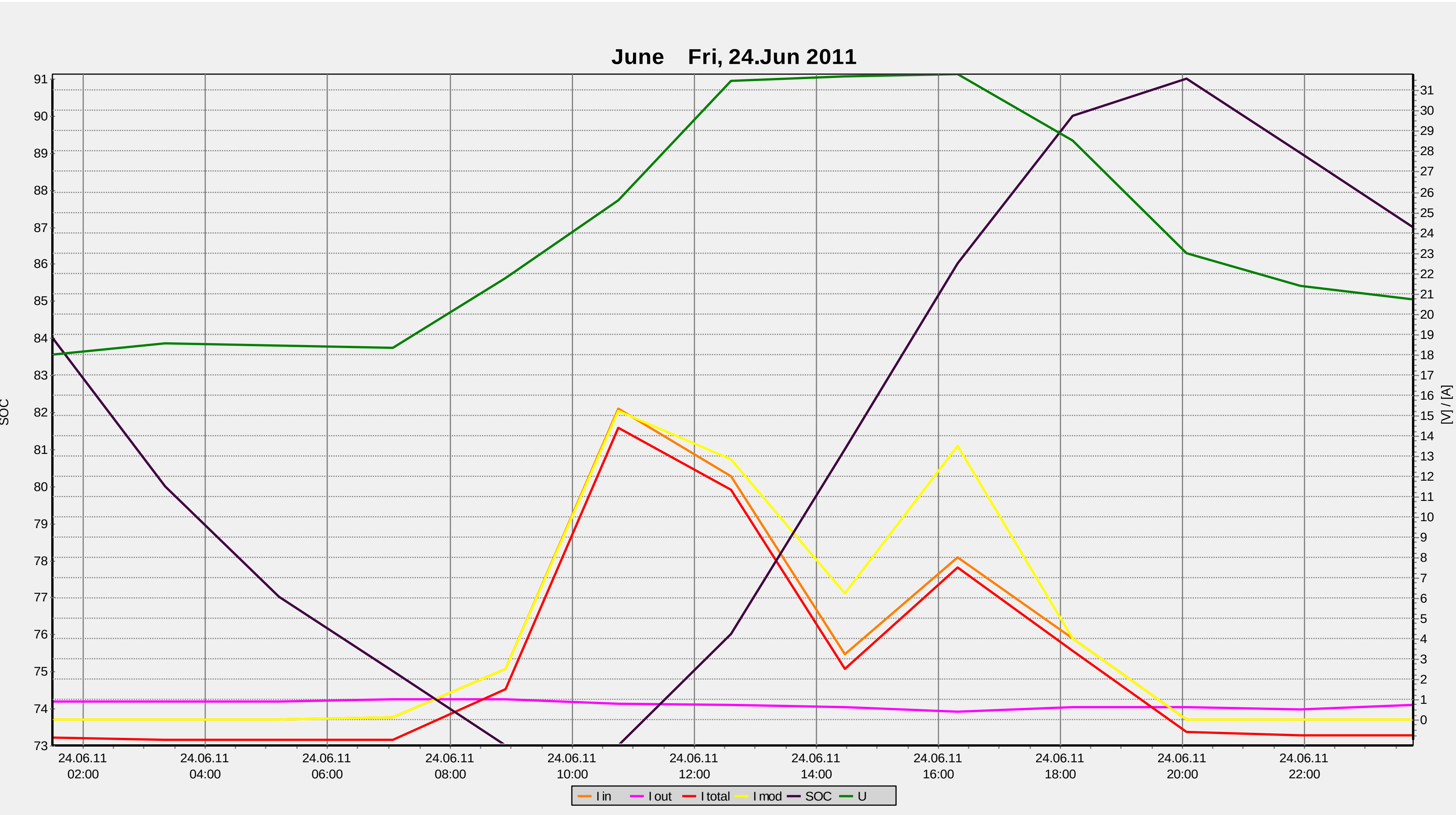


Figure 4. 24: Insolation on the 24th June, 2011 – Typical Winter Day Mikolongo

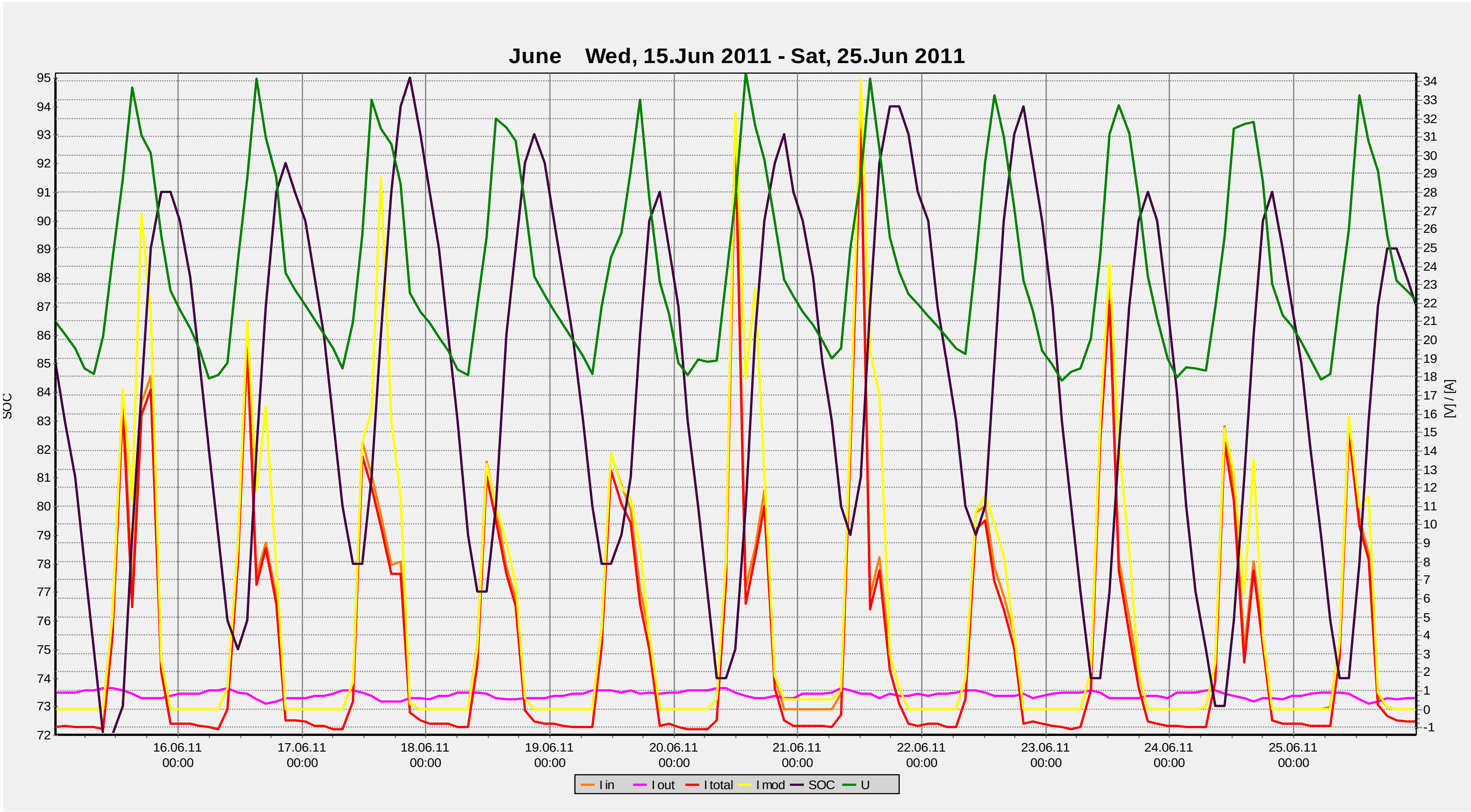
In this section the behavior of the insolation that had fallen on Mikolongo CRED site on a typical winter day is discussed. Figure 4.24 shows the variation of insolation over a full, clear day in June at Mikolongo School. The curve is representing the global solar insolation falling on a square meter surface area. The peak rate of incident solar energy occurs around noon and is 650 Watts per square meter. Over the full day, 4.78 kilowatt-hours of energy had fallen on every square meter of the surface as represented by the area under this curve.



I in Charging Current I out Discharging Current I total Resultant Current from Charging and Discharging Currents SOC Battery State of Charge U Battery Voltage

Figure 4. 25: System performance on the 24th of June, 2011 – Typical Winter Day at Malavi

In this section the performance of the solar PV system at Malavi CRED site on a typical winter day is discussed. As it can be seen from Figure 4.25, the battery voltage (green curve) decreased from a voltage of 27.71V around 6pm the previous day to around 18.45V at 7am on this day. After 7am, the voltage increased sharply to a voltage of 31.68V. During the same period, both the resultant current (I_{total-} red curve) and the module current (I_{mod}-yellow curve) decreased from 15.2A to 13.5A and 14.4A to 3.5A respectively. This is clear evidence that the charge controller was regulating the battery bank voltage normally. Both the battery bank and the total current curves show that the values decreased after 6pm. An explanation to this behaviour is that after 6pm there is absence of insolation but there is increased load demand due to community evening activities. Also worth noting is the state of charge of the battery. As the battery voltage increases, the state of charge also increases.



I in Charging Current I out Discharging Current I total Resultant Current from Charging and Discharging Currents SOC Battery State of Charge U Battery Voltage

Figure 4. 26: Performance for the system for 10 days (Winter Period – Malavi)

In this section the performance of the solar PV system at Malavi for a typical winter period over one week is discussed. As shown in Figure 4.26, the battery bank voltage (green curve) had greater variation for the entire 10 days period. The resultant current between charging and discharging (red curve) and that of the module current (yellow curve) had similar variations. However, it is shown that when the battery bank voltage was increasing at increasing rate, the module current and the resultant currents were decreasing. This was happening before the battery bank voltage reached the highest magnitude ever. Specific days like on the 17th, 21st and 25th, the charging and discharging sequence can clearly be seen and the charge controller was preventing a further charge or discharge of the battery.

It can therefore be summarized that in order to have a solar PV system fully sustained and operated over its entire expected life time, it needs to be maintained and repaired. Thus, a long-term monitoring and evaluation of a solar PV system provides a high degree of preventive maintenance of the solar PV system. In the above case, the system was monitored over a period of ten months and shows that it was compliant with the normal operating specifications of the system components used in this research study. This means that any deviations from the expected operating conditions would have entailed that the system was unhealthy and needed immediate attention. Therefore, such system information is vital since it could signal timely repair and maintenance/replacement of components so that the system should not be left out until it completely breaks down. Moreover, the solar PV technical performance data generated in this study will enable the design of more appropriate solar PV electrification systems in the future, either for home or community systems. Therefore, the author of this thesis argues that monitoring of operating compliance of solar PV system components is appropriate and provides a step forward towards system sustainability.

4.2.2.2 Overall Performance of the CRED Community Based solar PV Systems at Malavi and Mikolongo

4.2.2.2.1 Module Efficiency

This section focuses on how the system performed for a period of ten months. Thereafter, the section analyses the overall outdoor performance of solar PV system for two CRED sites (Mikolongo and Malavi) and gives a simple method of calculating the module efficiency. However, it is important to note that the systems at the two CRED sites have identical system components and have been tested in the real outdoor working conditions.

4.2.2.2.2 Calculation of Module Efficiency (*ή)*

The measurement of module efficiency has been reviewed in section 2.7.4.6 by looking at various types of models researchers use to analyze the module efficiency. The aim was to enrich the author of this research study the numerous methods of calculating the efficiency of the solar PV module. However, it should be noted that in this research study, the Steca Tarom Data Logger and the solar radiation sensor gave the required data for calculation of the module efficiency. In this case, the total collector area (ρ) of two Lorentz LA 75- 12S Monocrystalline panel was calculated and found to be 1.09 m^2. The monthly average solar insolation in kWh/m^2 (λ) was recorded by the radiation sensor and the collected data is shown in Table 4.11 & Table 4.12. In order to obtain the average panel generated kWh (μ), the product of solar insolation and panel area for each month was calculated and has been denoted as $\mu = \rho\lambda$. Moreover, the voltage (φ) at maximum power point (MPP) and the Tarom kilo Ampere hours (kAh) denoted as ψ for each month were recorded from Steca Tarom Data Logger and has been shown in Table 4.11 & Table 4.12.Therefore, the panel generated kAh designated by ε, representing the average input current, was calculated by dividing the average panel generated kWh with the voltage at MPP (i.e $\varepsilon = \mu/\varphi$). Therefore module efficiency for each month was calculated from the formular below:

$$Module\ Efficiency,\ \acute{\eta} = \frac{\psi}{\varepsilon} * 100\% \qquad (8)$$

Where ψ is the output current read from Tarom data logger in kilo Ampere hour

ε is the panel generated input current in kilo Ampere hour

ή is the module efficiency in percentage

4.2.2.2.2.1 The CRED Community Based Solar PV Module Efficiency

This section discusses the module efficiency of the solar PV systems for Mikolongo and Malavi sites. A comparative discussion is put forward focusing on how the sites performed in a period of ten months.

The module efficiency characteristics curves for the two CRED sites indicate that Malavi had higher operating module efficiency than Mikolongo (Figure 4.27). For the entire ten months period (October 2010 to July 2011), Malavi had its highest efficiency in the month of October (12.9%) and lowest in the month of June (10.77%). On one hand, Mikolongo highest module efficiency (12.84%) was also observed in the month of October and lowest module efficiency (10.54%) in the month of June. Also, it has been observed that the module efficiency for Malavi was generally higher than Mikolongo.

Malawi has two distinct seasons, dry season running from the month of September to April and the winter season that covers the month of May to August. It has been confirmed that the dry season is characterized by clear sky, hot temperatures and humid conditions while the winter season is characterized by cloudy sky and cool temperatures. It can be seen from Figure 4.27 that the module efficiency is affected by seasonal pattern. The module efficiency in the dry season month of October was high for both CRED sites. Coincidentally, this was the time when the insolation was high as well for the two CRED sites. For the month of October, Malavi and Mikolongo recorded insolation of 5.62 kWh/m^2/day and 4.11 kWh/m^2/day respectively. The module efficiency was high in October because many days of clear sky were recorded and this led to adequate generation of power from solar PV on daily basis. However, the module efficiency for both sites dropped from the month of November to April and this could be attributed to the fact that the period is characterized by hot temperatures and humid conditions. Consequently, it led to the presence of rainfall clouds that resulted in many cloudy days hence decrease in module efficiency. Moreover, it has been observed that there was subsequent decrease in generation of energy (kWh) from the solar PV array. Furthermore, it has been found that the lowest module efficiency for the two CRED sites was recorded in the month of June. This is because the month of June is characterized by many days of cloudy sky and cool temperatures hence inadequate generation of energy from solar PV.

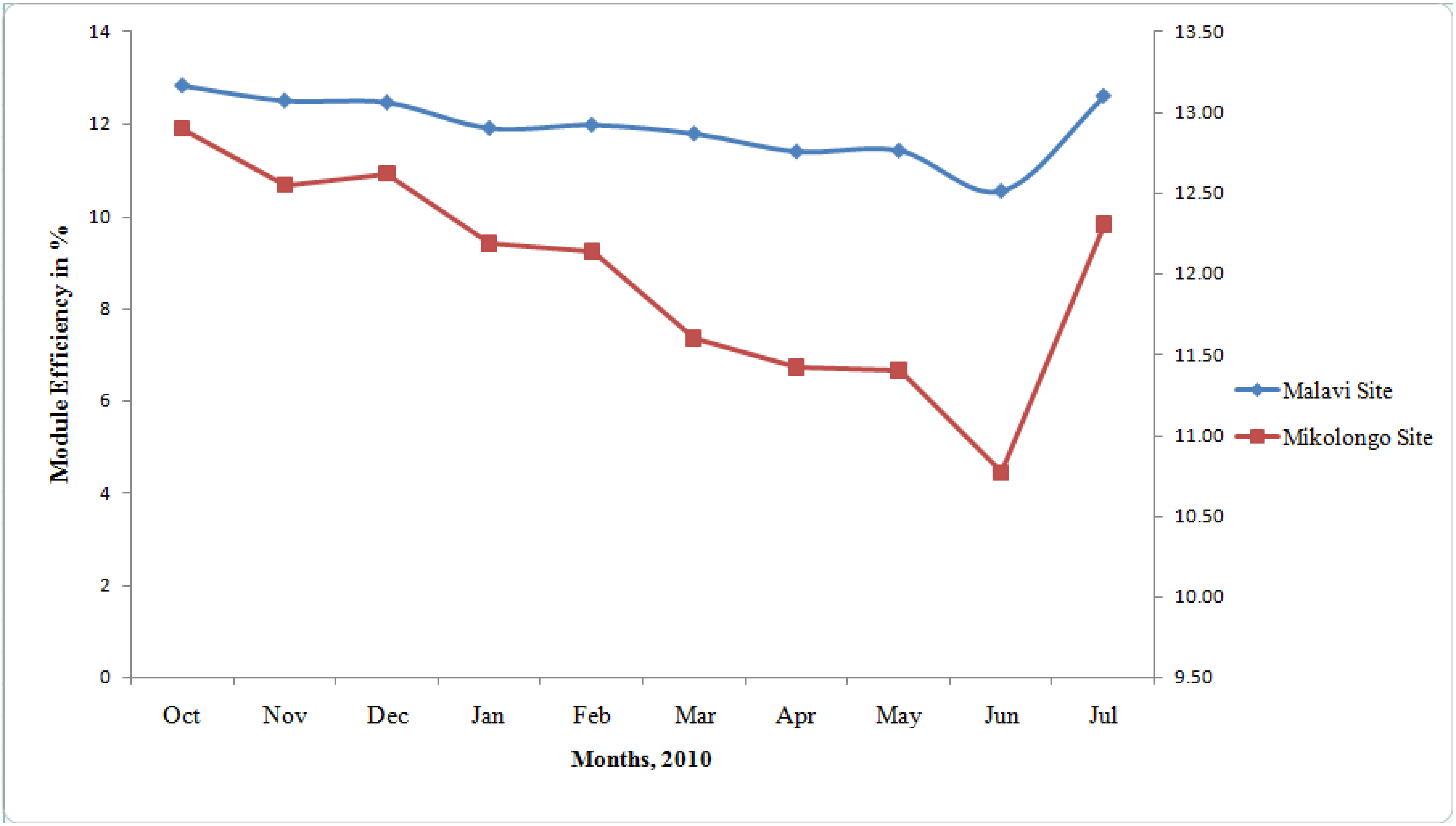


Figure 4. 27: Comparison of Module Efficiency at Malavi and Mikolongo

Thus, it can be said that solar PV systems in Malawi will yield highest efficiency in dry season due to presence of many days of clear sky. This period enables the module to produce enough current due to adequate irradiation. Moreover, since the power output is a function of irradiation, then it can be deduced that during the same period power output is high as well. On one hand, the lowest efficiency was observed in winter season as a result of many cloudy days. During winter period, the irradiation level decreases thereby reducing the module efficiency and power output. Therefore, all this lead to the fact that care should be taken when installing solar PV panels in order to optimise adequate generation of power from solar PV. In this case the tilt angle that the panel makes to the horizontal is critical. In dry season the sun is higher in the sky than in winter, and therefore the tilt angle for the panels could be made less in dry season. Besides, in winter the sun is low and the panels may be tilted more vertical. However, for most domestic installations the tilt angle is determined by the roof inclination and cannot be changed. Therefore, the optimal tilt angle for a solar system will be determined by the latitude angle at the site. In some cases support brackets can be used to adjust the tilt angle of the panels.

4.2.2.2.3 Battery State of Charge

The state of charge of a battery provides an indication of the amount of charge that is currently available in the battery and is given as a percentage. For example, a battery with a state of charge of 100% is fully charged and is empty when the state of charge is 0 %. Literature shows that for most batteries (Moo et al., 2008) the state of charge should not fall below the range of 20% to 40 % otherwise dangerous deep discharge occurs and this reduces the life span of the battery or can permanently damage the battery. During discharge, nominal acid density is being reduced and sulphates are placed on the battery plates. If discharge is too deep, this growth leads to harmful sulphation that reduces the battery’s capacity considerably, thus making the battery useless for energy storage. Overcharging the battery leads to uncontrolled gassing within the battery cells and the gassing depends on the acid temperature and cell voltage. The consequences are harmful oxidation processes and mechanical damages since gas blisters may knock out active lead material form the lead plates. The Tarom charge controller used in this research prevents the battery from falling below 11.8V in order to protect the battery from a too deep damaging discharge and at the same time preventing the battery from overcharging (above 13.7V) . This is why Tarom charge controller indication of state of charge is based on the actual capacity of the battery

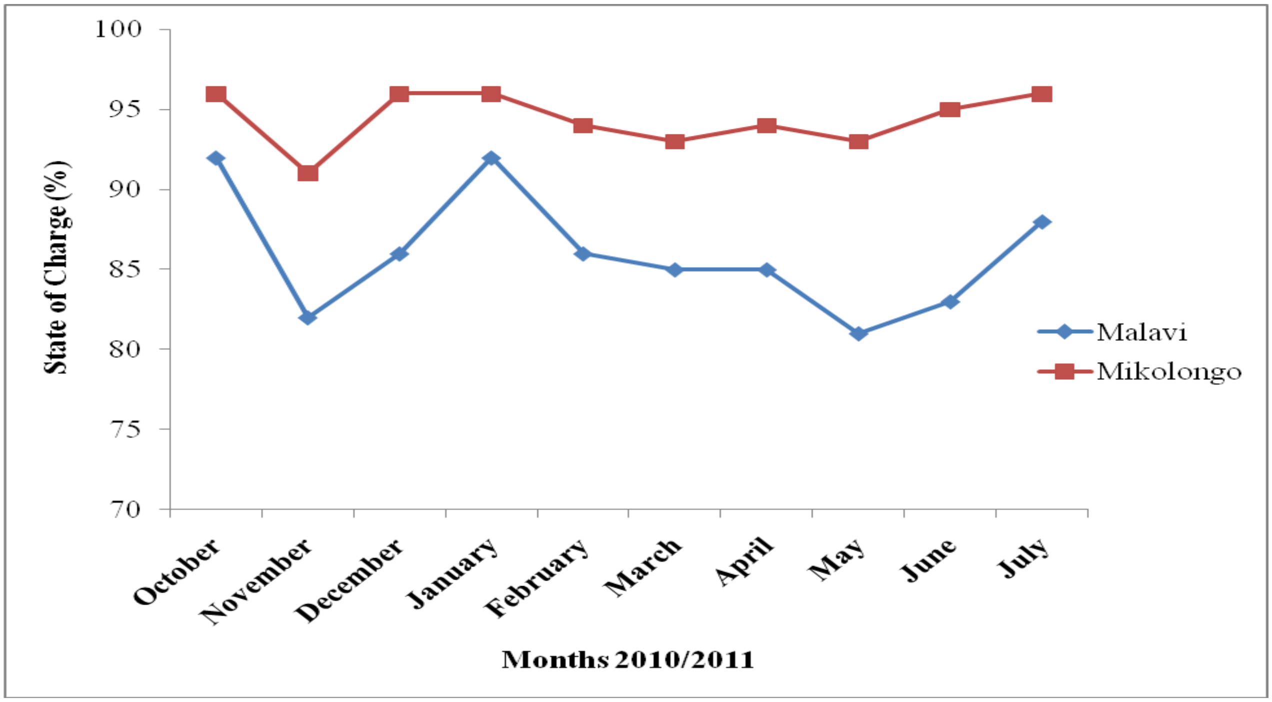


Figure 4. 28: Comparative Monthly Average State of Charge for Malavi and Mikolongo CRED Sites

As seen from Figure 4.28, the state of charge for Mikolongo is higher than that of Malavi. For a period of six months, Mikolongo state of charge of batteries was always above 90% registering a minimum of 91% and a maximum of 96%. On the other hand, the state of charge of batteries for Malavi registered a minimum of 82% and a maximum of 92% during the same period. It is worth noting that where the solar PV system is mostly loaded, the state of charge of batteries will be relatively low and where the system is un loaded most of the times, the batteries will remain in high state of charge. Seasonal variations also play a major role of the status of the state of charge of the batteries. The behavior of the state of charge of batteries (Table 4.11 & Table 4.12) for the two sites shows that for the month of October the state of charge of the batteries was above 90%. Coincidentally, this is the summer month in Malawi when insolation is high as well. During the same month Malavi and Mikolongo received an average monthly insolation of 5.62 kWh/m^2/day and 4.11 kWh/m^2/day respectively as shown in Figure 4.29. Therefore, the high state of charge of batteries is applicable during this period of the year. In the month of November, both systems indicate a drop in the state of charge of the batteries. A probable explanation to the drop in state of charge of the batteries is that during this period of the year, Malawi starts receiving first rains and the atmospheric clearness is reduced consequently affecting the state of charge of the batteries. Correspondingly, Madhlopa (2005) studied solar radiation climate in Malawi and found out that the mean monthly clearness index decreased from 0.64 in September to 0.46 in December. The author attributes the decrement in the mean monthly clearness index to the level of humidity and position of the sun relative to the site understudy. The author further argues that the period starting from November to April is rainy season in Malawi characterized by high humidity which reduces atmospheric transparency. It is also observed that the state of charge of batteries for both systems increased between December and January and started dropping after January. In both cases the systems' state of charge of batteries did not drop beyond their first minimum values (i.e. Malavi – 82% and Mikolongo – 91%) but remained near stable at the new low values of 94% for Mikolongo and 86% for Malavi for the months of February and March. Furthermore, another interesting fact worth noting is that the state of charge of batteries at Malavi remained lower for the entire ten months period than the one at Mikolongo. As previous discussed, this is attributed to the fact that Malavi system was more loaded than Mikolongo system. Therefore it can be said that there was more priority for charging phones and batteries at Malavi consequently the batteries remained in low state of charge from October to March while at the same time following seasonal variations. Apparently, the system at Mikolongo had fewer loads therefore the battery frequently reached full state of charge throughout the ten months period and it remained in high state of charge.

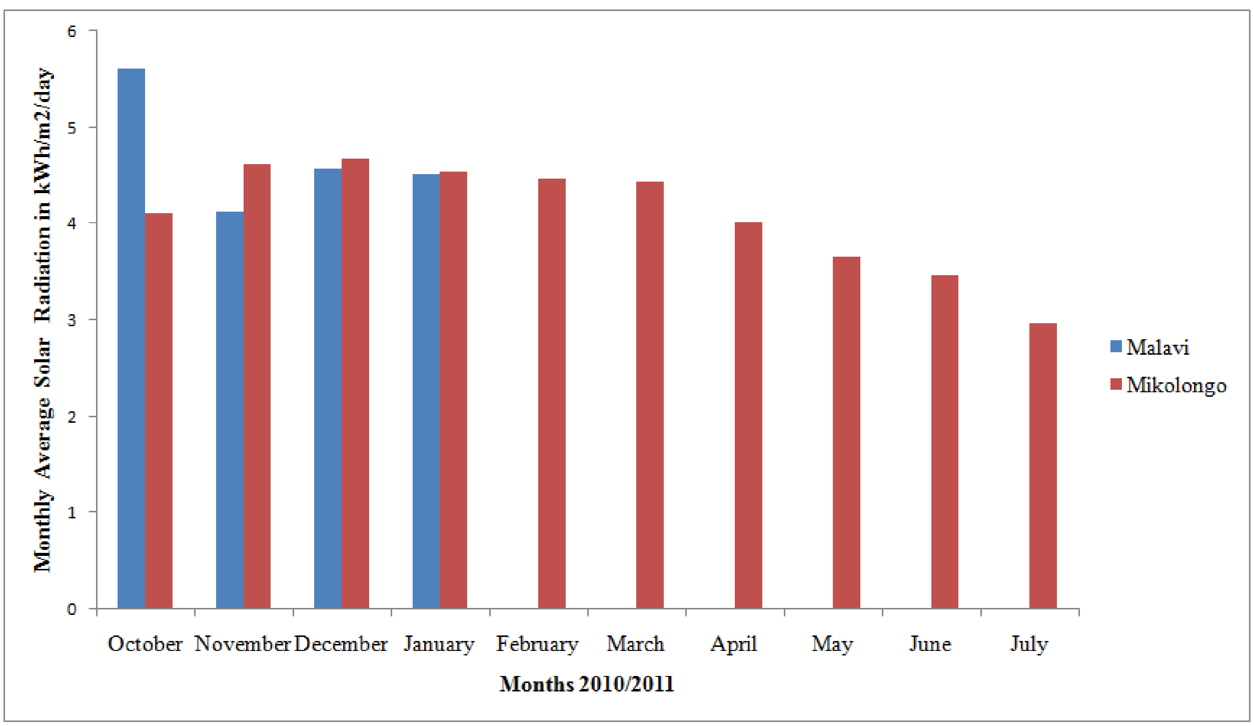


Figure 4. 29: Monthly Average Solar Insolation – Global Horizontal

Figure 4.29 shows the average monthly solar radiation for Malavi and Mikolongo. For Mikolongo, the insolation data was collected for a period of ten months while for Malavi was only for a period of four months. The reason for collecting data for few months at Malavi is because the radiation sensor had broken down and failed to log the data as anticipated. Besides this set back, the trend of the insolation data for the first four months for the two sites (i.e. October to January) has shown that there was small difference in the radiation levels. However, Malavi had shown an average solar radiation falling per Watt hour per square meter for the first four months of 4.7 kWh/m^2/day while Mikologo registered 4.5 kWh/m^2/day. The radiation level decreased for Mikolongo site from March to July and this is winter period in Malawi hence the sun is farthest from Malawi (i.e. located in the northern hemisphere) thereby resulting in a decrease in the radiation level.

4.2.2.2.4 System Usage

Table 4.11 and Table 4.12 depict results of energy use of the system at Mikolongo and Malavi respectively. The system at Mikolongo shows that the battery and load used an average of 52.4 % and 3.4 % of energy from the module respectively for a period of ten months. On one hand, 44.2% of energy generated by the module was not used for the same period. While the system at Malavi depicts that the battery and load used an average of 70.5% and 3.7% of energy from the module respectively for the period of ten months. It has been observed that for a period of ten months, an average of 25.8% of generated energy from the module was not used. It can therefore be argued that the module generated energy that was not used at both systems (two CRED sites) was being utilized for the functionality of the inverter. Moreover, it has been noted that the two CRED sites recorded less usage of the system.

Although both systems had shown less usage of the solar PV system, it has been noted that the system installed at Malavi had shown higher use of module generated energy through the load and battery bank than the one installed at Mikolongo. One explanation given to this kind of behavior is that the system at Malavi was optimally loaded as compared to the system at Mikolongo. The system at Malavi was used for lighting, phone and battery charging and also provided continuous lighting to the chicken cage. For a period of ten months, Malavi solar PV system charged 364 phones at a rate of 4 times a month. Additionally, the system charged 8 batteries in teachers' houses at the rate of 5 times a month for each battery. Consequently, this translates to 240 cycles of charging batteries for teachers' houses. Apparently, the system at Mikolongo was only used for phone charging and for a period of six months 241 phones were charged at the same rate as Malavi. In summary, the solar PV system installed at Malavi had shown better system usage than the one installed at Mikolongo.

However, the less usage of system at both sites can be viewed that the system was deliberately oversized. It can be argued that the deliberate over sizing of a solar PV system for a remote rural area could be advantageous because it can viewed, on one hand, as a deliberate means of enhancing the reliability of the system; however it is only applicable if costs permit. It is a desirable aim to do so because anecdotal evidence has shown that once the users' get accustomed to the technology, they forget its limitation and the system is subjected to abuse consequently the need for the system to be able to absorb any extra load. Besides, over sizing the solar PV will result in production of higher output than needed and the produced power is lost due to a fully charged battery bank (in case of Mikolongo).

4.2.2.2.5 Challenges in Collection of Technical Data

The study met some challenges at Malavi School, for the months of March to June; the solar radiation sensor logged erratically or failed to log the insolation data in some of the days due to battery failure. The battery in the radiation sensor was used for powering the logging sequence at set time interval. When a new battery was replaced, it was thought that the logging of solar insolation data would resume. Unfortunately, periodic checks on the battery by a voltmeter revealed that the battery drained very quickly due a faulty electronic card. The battery voltage drained from 9V to as low as 0.078V within a period of 48 hours. Therefore three months of solar insolation data for Malavi School was erratically available for analysis and this coincided with the winter period. However, since the technical performance of the solar PV system study was conducted over approximately a period of ten months, the solar insolation data collected for Malavi though erratic but was adequate to assess the performance of the system.

4.2.2.3 Conclusion of Technical Sustainability of CRED Community Based Solar PV Project

As it can seen from above, the research study of the CRED community based approach model focused on assessing the solar PV system technical data by looking at specific parameters such as SOC, efficiency, solar insolation, system usage etc. So far it can be concluded that the performance monitoring of the solar PV system was fairly good and was key to the sustainability of the system. The monitoring of the system components was significant because it provided a window of assessment of the solar PV system components used in the CRED project. It can be said that the operation of the solar PV system as revealed by the results depict a satisfactory operation of the system components for the entire period they have been operational. The system components operated well and always met the designed load. The charge controller properly regulated the battery bank by effectively allowing the charging and discharging sequence at pre-determined set points thereby increasing the life expectancy of the battery bank. The battery voltage was regulated between a minimum of 11.8 V and maximum of 14 V. Also the fact that Mikolongo depicts less usage of the system, can be viewed as advantageous since the solar PV system would allow for load growth and flexibility in user's needs in the near future to maximize its potential.

Another significant parameter that was monitored closely is the SOC of the battery. Indeed, most typical rural systems used for domestic lighting and communal services in developing world constitute PV modules, charge controller and batteries to store electricity generated by the PV modules. It is noted that the batteries plays several major tasks in the system such as providing the PV system autonomy of several days without module generation, extending the electrical service hours to night time periods and absorbing short time intermittences of sunshine. Despite playing these major roles batteries are the weakest element in a PV system. They can easily be damaged by overcharging and discharging, and improper operation and maintenance practices. Therefore it is with this background that performance evaluation of the batteries is required to assist the user maximum utilization of the system and periodic assessment of the system to assess if it meets design expectations. A good number of renewable energy technology models such as those discussed in section 2.7.4.5 have been developed to assess performance of solar PV systems. However, in this research study, indicators of battery charge history was included to avoid risking battery life and one such battery parameter was the monitoring of State of Charge. This has been vital in improving the battery performance because it alerted the users and the technician when inverters could be powered down and the load could be disconnected to save the life of the batteries. The charge available in the battery was monitored by the Tarom Charge control unit for close to one year and the data so far collected has shown good performance of the batteries. The SOC remained fairly above 90% most of the times.

It should be noted that Lasnier et al., (1989) argue that the state of charge can be used to predict system performance of a photovoltaic system. The authors say that the performance of a solar PV system at any given time or during any time interval is dependent on state of charge of the storage media and electrical energy flow from the modules at that time interval. On the same note, the authors confirmed that state of charge of the solar PV system will fluctuate as a result of change of radiation despite the load remaining constant. Thus, it is concluded that the reflection of the performance of a solar PV system in relation to state of charge about a daily or seasonal mean exhibit a diurnal cyclic variation. Similarly, the daily plots for solar PV system at Malavi and Mikolongo show that the battery state of charge was not changing considerably for each day because the batteries were fully charged both for that particular day and the one before. Indeed, this is evidence enough that the battery had lower charge/discharge rates and a shallower daily depth of discharge which is associated with an increased recovery time of the battery from a low state of charge consequently improving the life span of the battery.

The preceding sections looked at the performance of the solar PV system by analysing the technical parameters. In the final analysis it has been found that the State of charge for both Mikolongo and Malavi was well above 80% for a period of one year. However, Mikolongo had a higher steady SOC averaging 90% for the same period. It however, important to note that during the same period, over 50% of monthly average energy was used for both sites with Malavi recording high battery average energy use of 70.5%. An equally significant aspect is the analysis of the solar radiation of the two sites. It has been observed that the monthly average solar radiation for Mikolongo and Malavi has shown smaller difference but both sites registered high values of solar radiation for the months of November, December and January. However, a point of interest is Mikolongo which has shown an insolation level of 5.62 kWh/m^2/day and compares well with insolation level of some of the SSA countries shown in Figure 2.2. Another important point worth noting is that the average solar insolation level for Malavi is based on the four months starting from October to January. The reason being for the months commencing February to July, the insolation level was erratically captured due to a faulty radiation sensor at the site. However, the level of solar insolation captured has demonstrated that for Malawi, the insolation is higher during dry season and lower in winter season.

Having considered the insolation levels at both sites, it is reasonable to consider the module efficiency of the two sites. It has been observed that module efficiency for Mikolongo and Malavi were highest in October. Malavi registered an efficiency of 12.9% while Mikologo was

12.84% and these values of module efficiencies compare well to those shown in Table 2.5 for the same kind of solar PV cells. Moreover, the high values of module efficiencies coincide with a time when the insolation level was also high for the two sites. In addition, the module efficiencies for the two sites has shown the same pattern for the entire 10 months period, that is, rising and falling at the same time and averaging well above a module efficiency of 10%. It is however important to note that the research study was conducted within a period of one year and monitoring a longer period of time will be required to make judgement on the long-term sustainability of these systems from a technical perspective.

4.2.2.4 Solar PV System Design Verification

It should be noted that in the CRED Community based approach for provision of energy to rural population, the solar PV design did not have detailed verification exercise to determine whether the various components used in the installation performed according to manufacturer's specifications. This was because the timescales and budgets could not accommodate such an exercise. Despite the aforementioned, to some extent, several field inspections were performed to evaluate the installation quality and correctness for the CRED photovoltaic systems. The field inspections assisted to verify that the systems were designed installed and also were consistent with industry practice, standards, codes, and operational requirements. In this case, the Energy Committee members and the CRED Managers were conducting visual, electrical, and mechanical inspections but were not limited to, evaluating and reporting the following where applicable: damage to photovoltaic modules, torque of electrical and mechanical bolted connections (spot check where specified), corrosion protection, integrity of photovoltaic module mechanical and electrical connections (random), damage to photovoltaic modules, damage to support structures, integrity of installation and support of electrical cable and conduit systems, integrity and completeness of wiring and installation in compliance with applicable codes and standards. Of course, some of the listed activities above were documented in log books and appropriate actions were taken where applicable so that the systems should be compliant with codes and standards.

On one hand, another performance parameter that is deemed to have been verified in the course of assessing the performance of the system is the module efficiency of Monocrystalline solar cell. It has been verified that the module efficiency is really a reflection of the influence of the irradiation and of the cell temperature on the I-V characteristic of the PV module. It was observed that the module efficiency at Standard Test Condition (17%) as specified in the data sheet for Monocrystalline panel technology was higher than the outdoor measured efficiency (12.9%) in the summer month of October with almost 24%. The most likely explanation is that the efficiency of the panels is actually less than the rated values, that is to say, measurements are acquired in realistic weather conditions, i.e. with panels subjected to severe weather conditions such as hot temperatures, dust etc. Thus, care should be taken when deciding panel technology to be installed in areas of extremely high irradiation.

Furthermore, the charge controller operation was closely monitored by using the Tarom Data Logger model. According to the Tarom Charge Controller specification data sheet, it has been specified that the high and low disconnection voltage cut off points are 13.7 V and 11.8 V respectively. It has been observed that the Charge Controller was regulating the battery voltage within the high and low voltage disconnection points.

5 Chapter 5: Conclusion

The purpose of this research study was to look at factors that can address sustainability of off grid power in developing countries: A case study of Malawi. Therefore, in this chapter the author draws conclusion on how challenges of off grid power should be addressed for the off grid power systems to remain sustainable. Also the experiences gained in the Community Rural Electrification and Development project forms part of the conclusion. An effort is made to expose factors that are crucial to off grid power sustainability in developing countries with reference to the CRED community base approach model study results. Indeed, the results have a link to the problem statement. It should be noted that although some discussion centred on the module efficiency of the CRED solar PV system, it is the opinion of the author of this research work that sustainability comes first before efficiency of the system in order to keep good quality life rolling out as result of the installation of the solar electricity. Moreover, this chapter summarizes the whole work, findings; and highlights the contributions the research has achieved and its recommendations. Finally, the chapter recommends further work to be done which should follow this work.

Electricity is vital element in the development of any community or nation. Access to and use of electrical energy is one of the many factors that dictate the growth of development. This research has shown that in Sub Saharan Africa and many other developing countries around the world, electrical energy is either inadequate or sometimes completely unavailable. The main finding of this research is that solar photovoltaic as a source of energy is highly suitable intervention in provision of electrical energy for improvement of health care and education systems. It is important however to note that solar PV needs to be properly managed for it to remain sustainable in order to provide reliable power at all times. In this research study, the CRED Community Based Approach model for Sustainable solar PV was designed, tested and reviewed to demonstrate the solar PV sustainability. The model has demonstrated that it has potential to provide basic energy service to rural communities in sustainable basis, economically, socially and environmentally and above all ultimately improve living standards and lift people out of poverty. However, it should be noted that the project had its own challenges.

5.1 Social and Institutional Sustainability

Under this section, conclusions are presented based upon the CRED community based approach for sustainable solar PV that demonstrated potential to contribute to social and institutional sustainability of the solar PV systems.

5.1.1 Participation of the Local Community

The involvement of local community at early stages of planning and implementation where CRED solar PV system installation have been located is a catalyst to generate ownership that helps achieve long term success of the project. It is envisaged that since the local communities are beneficiaries of the energy projects; they must have a choice of energy needs if energy policy and services are to meet their expectations and provide long term solutions. In addition, introducing technology into the social reality of rural communities is a task that cannot be addressed solely by technical means. It is a social task and consequently needs social preparations for the project activities. Ignoring of this basic experience leads to unresponsiveness to the users' demands and to a high probability of project failure. To ensure proper deployment of solar PV systems and long sustainability of the CRED community base approach model, communities were identified using the existing relationship of the local community with Scotland –Malawi Health Initiative programme. Regular visits to the community raised awareness of the CRED project. Sensitization meetings took place and workshops were held to identify energy priorities. These meetings had a formal structure dictated by the community and included Traditional Authorities, village headmen, village elders, church elders, and representatives from the education authority. Random sample questionnaires were used to baseline existing energy usage and potential enterprise schemes.

5.1.2 Cultural Acceptance by End Users

Results and author's own observation have shown that in all CRED centres, the strong indicators that relate to the degree of acceptance of the solar PV technology have been: (i) the local community with assistance of the energy committee have initiatives for maintenance and repair of the system such as careful handling of the technical devices (e.g. regular cleaning of panels, regular inspection of system components etc (ii) taking over obligations regarding solar PV system (e.g. log keeping, attending to solar PV training sessions, data reporting etc) (iii) Energy committee members meet regularly and take responsibility for keeping their communities informed of developments. However, in one of the CRED sites batteries and a dc refrigerator were stolen by members of the community. This is one of the sites where income generation was very low and the system poorly maintained by the energy committee and it had stayed for longer period of time without functioning due to damaged batteries during system upgrade. The author's own observation is that the community was frustrated to secure a system that was not functional hence there was high chance of the system being left unattended and as a result, it was vulnerable to theft. In summary, it is important to note that communities that are beneficiaries of off grid power should be able to take ownership and responsibility for security, management and maintenance of the off grid power systems and above all there should be cultural acceptance of the off grid power systems for the systems to remain sustainable.

5.1.3 Training of Consumers in System Use, Safety and Maintenance

A review of case studies in Sub Saharan Africa has shown that solar PV systems were successfully installed in the rural areas however there was a problem to ensure sustained operation of the system. It is important to note that a number of authors have given significant evidence that one of the major factors to failure of solar PV system has been lack of maintenance. The CRED community base approach model case study in Malawi has shown that rural electrification is a complex issue and for it to remain sustainable, it should encompass good planning strategies, adapt local conditions and incorporate local communities at their inception. To address this problem, a number of training workshops on solar PV system technology were carried out mainly targeting the Energy Committee members who represented community stakeholders. Since each of the seven villages has a 10 member Energy Committee, approximately 70 local community members were trained on solar PV system use, safety, maintenance and limitations of the PV technology. As such training enhanced local technical support in the area of service and maintenance of the solar PV system. In addition, during solar PV training sessions a number of topics on solar PV systems operation, safety and maintenance were covered in elementary ways and include definition of solar PV module and its maintenance, measuring and recording of battery voltage, ways of keeping a battery bank well insulated, clean and free from rodent damage, checking battery electrolyte level and topping up with distilled water, checking wiring connections from the solar PV modules, charge controller, battery bank and inverter, ensuring transparency and accountability of generated funds, fault reporting procedures, protection of the solar PV system , accurate collection of social and economic data, keeping a list of all the maintenance work and the spare parts exchanged and bought. Additionally, the energy committee members were equipped with tool box set as part of their skills training. At the end of the training session, each energy committee group that represented each CRED site were given a tool box that included: a multimeter, a screw driver set, spanner set, pliers and insulation tape to repair any small wiring problem that may arise in the use and operation of the solar PV system. The objective behind training sessions and distribution of tool box was to bring additional great benefit for the long-term performance evaluation and sustainability as well increased interest of the people in their solar PV system. In order to ensure that there is coordination amongst the CRED sites, the CRED project included a local based Field Coordinator whose responsibility is to coordinate social and technical activities such as support enterprise activities, monitoring community log books and overseeing system maintenance and management.

5.2 Economic and Financial Sustainability

Income generation must be encouraged to safe guard operations and maintenance of the system. Therefore appropriate financing schemes which safe guard the long term operations are essential. The results obtained in this study show clear evidence that the project has transferred knowledge to solar PV users and has given a starting point for self sustained economic growth. Above that the project has brought new paradigm shift that using a variety of frameworks and financing mechanisms can be a catalyst to alleviate poverty and create sustainable and clean economic growth. For example, results of this study show that the local community through the elected energy committee had direct control of the affairs of the solar PV system. The energy committee has been collecting fees for small income generation activities such as battery charging, phone charging and sells of cold drinks that can be utilized to maintain the systems and carry out other developmental activities in the local community. The Local community was able to generate close MK130, 000 from battery and phone charging and sale of cold drinks in one year from the seven solar PV installations having installed capacity of approximately 1kW. Thus as already said in section 4.1.1.1 (a), the revenue analysis from the CRED community based approach model can only be expected to cover on-going running costs and recovery of full life costs is not feasible.

Above that the energy committee has been entrusted to account for the funds generated through the use of the solar PV system foreseeing that large sums of funds are being collected. Meanwhile most of the CRED centres have opened up bank accounts to save funds generated from income generation activities. Therefore, the aforementioned can be envisaged that the local population has been acquiring basic accounting skills besides pursuits in income generation.

Additionally, the CRED project management has negotiated with a number of finance institutions in Malawi that would support the sustenance of the system through delivery of soft loans to the energy committees to carry on with income generation activities.

5.3 Technical and Operational Sustainability

This section looks at quality assurance systems that were put in place for the CRED community base approach model for sustainable solar PV and are discussed below.

5.3.1 Reliable System Components

One of the significant features of the present PV status in Malawi is that there are several entrepreneurs largely undertaking supply and installation of PV systems. The majority entrepreneurs sell solar PV components directly to end users often without advice on system design or installation. The final outlet for PV components is usually a trader who provides no warranty and who is not qualified or experienced to provide installation and sizing advice. This is believed to have a serious effect on quality of installation as well as system sizing. Apparently, most of these small entrepreneurs execute contracts in government, private homes and Non Governmental Organizations. The effect has been an unacceptably high incidence of system failure in the field - attributed to poor product quality, poor system integration, poor installation standards, absence of after sales service infrastructure and most importantly no user financial commitment to equipment supplied. To depart from this tradition, the CRED community base approach model for sustainable solar PV system incorporated quality assurance system at the design and implementation stage of the solar PV installations in southern part of Malawi. The equipment used in this project such as the Tarom Charge controllers, panels, batteries, inverters and other solar PV electrical accessories were procured from reputable solar suppliers and considering electrical specifications suitable for Malawian conditions. In general the electrical equipment has been of good quality, reliable and there has been strong emphasis to use government certified reputable solar PV equipment suppliers. Furthermore, the installations were carried out by government certified solar PV installation companies with proven track records in solar PV installation and maintenance. These have been providing timely after sales service. This has greatly improved the prospects for the long-term sustainability of the solar PV system. On one hand it has been observed that even though certified installers have been used in the installations, they have sometimes deliberately not followed standards procedures for installation in order to maximize profits from business contracts at the expense of sustainability of the system. This is done by using poor quality installation materials that do not have proper specifications and sometimes by using un qualified technicians. Indeed a classic example is the CRED project, although reliable parts were used in the model, it has been established that out of a total of seven solar installed CRED sites, three sites experienced problems with batteries after operating close to three years and the rest are still operational. Some of the certified installers mixed poor and good batteries during installation and up grades of solar PV systems in CRED sites hence the batteries were damaged in some sites and did not last for five years as expected. Of course, anecdotal evidence lead to the fact that solar PV batteries life span is close to five years if properly maintained.

5.3.2 Local Capability for Operation and Maintenance

An energy committee has been put in place to operate and maintain the solar PV systems. The systems have been routinely monitored and any failure or malfunction of the solar PV system was reported to the trained technician for fault diagnosis. In the CRED community based approach for sustainable PV system, there has been a four level reporting procedure in the event a solar PV has broken down. The first stage involved the energy committee that operated and maintained the system on daily basis. Once a fault was identified, it could either be rectified if the fault was minor or reported to the locally based Field Coordinator if the fault was beyond the scope of the Energy Committee. The second stage involved the Field Coordinator who undertook visits to the CRED sites to assess the gravity of the fault and offered technical advice if were applicable. If the fault was beyond the scope of the Field Coordinator, a report was sent to Project Mangers at Polytechnic to provide the final technical advice and feedback was sent to the Field Coordinator on how to repair/maintain the system. In addition, the installers were also contacted to have the system repaired immediately more especially when the system was within warranty. The author’s own observation has shown that the installers used in the CRED community based approach model project failed to honour repair/maintenance obligations within the warranty period. As a consequence, the reporting procedures have not been effective enough more especially between the Energy Committee and the Field Coordinator. It has been observed that it takes longer time for the Energy Committee to report faults to the Field Coordinator thus exposing the system to be on outage for longer periods of time resulting in loss of productive use of the system. In addition, it has been observed that the local people consider solar PV as an advanced technology so much so that even simple faults like replacing a burnt bulb have not been rectified in time. Members within the energy committee do not shoulder the responsibility to rectify minor faults for fear of 'blame game'. For example, if one replaces a burnt bulb and something goes completely wrong within the solar PV system, that particular person will have to shoulder the responsibility of damaging the system. Therefore, even minor faults will not be corrected immediately and will wait until a qualified technician is available to do repairs and maintenance.

Whilst the discussion in the preceding paragraph looked at warranty and reporting procedures, this section will concentrate on how the equipment used in the CRED model solar PV installations provide simple means of operation and maintenance. The charge controllers used in the installation of solar PV in the community base model have been chosen on user friendliness because they provide easy monitoring of the solar PV system parameters. The Steca Charge controller provides the system parameters to be monitored at glance on a Liquid Crystal Display (LCD). The status of system parameters provides a quick conclusion on the performance of the solar PV system at that instant of time or during a stated operating period. For example, unexceptionally high loads that are not attended for a solar PV system can shorten the life span of a battery bank or on the other hand a current record gives a possible deterioration of the solar panel or partial shading. Therefore, to avert this problem, Steca Tarom Charge Controller installed in CRED community base approach has a facility to recognize low battery voltage or prolonged high loads that cause stress to the solar PV system. The results in this research show that the battery bank voltage was consistent around 13V. This is evidence enough that the performance of the installed systems was reasonably normal and the solar PV system could absorb more loads than anticipated however additional loads on the system would require expert advice.

5.3.3 Performance System Monitoring

Performance system monitoring of the solar PV system has been established and is on-going and shows great potential in supporting long term system sustainability in terms of preventive maintenance. The Polytechnic staff and the Village Energy Committee members take full control of this process. For instance, the status monitor on the Steca Charge Controller (Green - switch

ON Loads) and (Yellow - switch OFF Loads) enhances the ability for the energy committee members entrusted with solar PV system to switch ON/OFF loads depending on the performance of the system and allows the energy committee members/trained technician to record daily performance data. This is an indication that the people are allowed to learn the principle of operation of the technology and at the same time adapting the system to their needs. Furthermore, the system has also been the responsibility of the energy committee and local community, along with monthly field visits from Staff from the University of Malawi – The Polytechnic and consequently all those involved have learnt about the technology and the required maintenance and limitations of the technology. Another interesting result that was obtained in this study is that the Monocrystalline panel technology installed at Malavi in Chiradzulu District (generally cool climate) and Mikolongo in Chikhwawa District (generally hot climate) performed fairly well for one year despite minor differences in their overall average module efficiencies i.e. Malavi 12.9% and Mikolongo 12.84%. This result suggests that Monocrystalline panel technology can be used in locations with hot and cool climates of Malawi with stable performance. Although the Multicrystalline solar module performs well than Monocrystalline, as indicated in the literature review in section 2.7.4.6, the author was constrained to use the available budget, resources and time in the study. The budget allocated to this research study did not cover installation cost for Multicrystalline solar modules hence the choice of Monocrystalline solar modules which were available in the CRED sites. Despite this fact, the choice of monitoring the performance of Monocrystalline solar modules in this research study has demonstrated that the Monocrystalline module works equally well under Malawian weather conditions. Therefore, research work of this kind should be carried for longer periods of time in order to draw concrete conclusions about operation of crystalline solar modules in the hot and cold climates of Malawi.

5.3.4 Sound Design of System Configuration

The system that powers lighting points in classrooms at Malavi and Mikolongo has been designed to run all lighting for 4 hours each evening (555WH) plus provide 110Wh of AC electricity each day for charging mobile phones and a laptop. Two days of autonomy are also accounted for in the design. At Malavi a battery charging station has been installed at teacher's houses. The teacher's houses have a simple lighting system of two 9W DC bulbs connected to a 50Ah 12V lead acid battery. Every two days, two batteries of low voltage (between 11 and 12V) are brought to the charging station and connected in parallel with two permanently connected batteries. The battery bank equalizes slowly over time and no damaging currents have been measured. Measurements show the initial current at connection of an empty battery to only be around 5A. The charge controller senses a low battery bank voltage and applies charge current appropriately from the PV array. It takes approximately one and a half clear days for the four batteries to all fully charge to 13.7V. Generally, for the past three years the system has shown minimal failure and the technical performance of the system has been good. Also another important fact has been the continuous monitoring of the solar PV system has given a window to improve the design of the dc lighting system and the battery charging station. For example, the solar PV system design for Malavi teachers' houses did not incorporate low voltage battery cut off point. As a result there was a risk that the batteries would completely be discharged due to over use and get damaged. Therefore, re-designing the system would be appropriate to enhance system sustainability.

5.4 Environmental Sustainability

Many authors have acknowledged that solar PV contributes to the environmental sustainability because it is one of the clean technologies. Despite the fact that solar PV as an alternative energy source has less harmful effects on environment when compared to other sources of energy (fossil fuels), anecdotal evidence points to the fact that life cycle analysis of batteries and modules for stand-alone PV systems are responsible for most of the environmental impacts. It is highlighted that batteries have short life span and are constructed from large amount of metal. Furthermore, batteries require significant amount of energy and raw materials for their production. It is said that during material processing for production of batteries, gas emissions are released though fewer than those of conventional fossil fuel technologies. Of central concern is that lead acid batteries pose a potential threat to human health and environment. The two components of lead acid batteries have highly corrosive sulphuric acid and lead which has been linked to nervous system damage to humans and animals. Therefore, poor disposal of lead acid batteries such as in landfills and garbage bins will expose humans and animals to health risks.

Also anecdotal evidence from literature has shown that routine and accidental discharges of pollutants in solar PV system have been recorded. It has been noted that some panel technologies such as Multicrystalline and Monocrystalline release harmful substances that pollute the air. In addition, it has been noted that Copper Indium Deselenide (CIS) and Cadmium Telluride (CdTe) panel technologies production processes include small quantities of toxic substances. Therefore, in such cases, there is potential risk of harmful chemicals being released into the environment more especially where an array is in close contact with fire. Thus, there must be emergency preparedness and response in case of an accidental fire or exposure to heat.

Furthermore, it has been noted that large scale exploitation of solar PV could lead to other undesirable environmental impacts in terms of material availability and waste disposal. The end of life cycle of solar PV systems generate substantial amount of waste in form of used modules which need to be landfilled. This calls for the need to dispose their equipment and accessory materials properly in order to reduce harmful environmental impact.

Moreover, transporting batteries to rural areas where the solar PV systems are to be deployed comes with its own challenges more especially when batteries are to be transported through poor terrain. The batteries might get damaged in the course of transportation due to poor handling and this may endanger the health of the people involved in the transportation of the batteries and above all release harmful substances into the environment that could harm the environment.

Thus, it is important to note that in the CRED Community Based Model Approach there have been a number of cases where the lead acid batteries have permanently failed, for this reason, CRED managers discussed to dispose used modules or damaged batteries by using proven recycling technologies. It was discussed that glass waste from modules contain adequate plastics (EVA foil) that can be accepted by glass recyclers in Malawi or neighbouring countries in order to demonstrate potential steps towards environmental sustainability. Also, the other proposed method has been to promote the use of air emission or ordour control equipment.

5.5 Challenges of CRED Community Based Project

This section will give a summary of some of the challenges the CRED community based approach project encountered and are as follows:

5.5.1 Inadequate Generation of Maintenance Funds

Generation of funds for maintenance of the solar PV system was well captured at the design of the CRED project. This included tariffs charged at community level for mobile phone charging and sale of cold drinks, facilitated by the solar energy installation. The income is kept in a central fund for maintenance and other future uses. However, the maintenance funds generated is not adequate enough to meet repairs and maintenance of the solar PV system and only some of communities managed to bank reasonable sums. This has been the case because the systems broke down before sufficient savings could be made. The revenue streams at Malavi and Mikolongo were however close to providing sufficient sums to replace the battery banks after a few years they have been operational.

On one hand, transparency and accountability of funds still remains a major challenge even besides income generation being low. For example, generated funds became source of suspicion and conflict between the energy committee and people outside the energy committee. The energy committee was not transparent with funds realized through the use of the installation and gave themselves incentives for their roles they played as members of energy committees.

5.5.2 Failure of Batteries and Light Bulbs

It has been noted that in some CRED sites there has been regular failure of light bulbs and batteries. Since the replacement cost is high and there was absence/inadequate maintenance funds, the burnt light bulbs have not been replaced to bring the same quality of light in the classroom blocks. Therefore, it is important to seek battery and light bulb technologies that have long life span than the one currently in use.

5.5.3 Community Participation

It is known fact that for any project to be successful in the remote rural areas there should be high levels of participation in the community where the project has been deployed. Participation leads to increased capacity for ownership, autonomy and sustainability strived for in the project objectives. However, it has been observed that members of the community out with the energy committee have low levels of participation or ownership in the CRED project. Therefore, the project should consider wider community participation and benefit.

Nevertheless, despite challenges faced in the CRED community based approach model for sustainable solar PV, the experience has shown that the model has demonstrated that solar PV has considerable potential to contribute to meeting the energy needs of rural and remote communities in Malawi. However, to ensure that solar PV remains sustainable in rural areas, attention must be paid to local ownership with an appropriate mix of individual and collective ownership and management. Moreover, providing a mix of offerings that are appropriate to needs and financial capacity, building local skills for the system's operation and maintenance, quality assurance and ensuring locally produced and accessible components are also important in developing support for this technology. Also providing electricity for meeting lighting needs of households and rural markets can yield positive results, including improvements in quality of life and increasing income and employment opportunities. These impacts can mean that a developing country can more rapidly achieve the Millennium Development Goals. The community based approach for Sustainable PV systems tested in the CRED project in southern part of Malawi could be equally applicable to the other developing countries with similar socioeconomic conditions. However, replication of the CRED model should look at not only provision for lighting to the rural people but uplifting their economic status greatly by provision of large scale solar power for irrigation and other motive power. This calls for Malawi's sustainable energy plan that is inclined heavily on generation of energy through hydroelectric to seriously consider exploring solar energy potential in the short and medium term as a source of energy on a large scale. It can be strongly emphasized therefore that the inclusion of solar PV systems in Malawi's energy sustainability plans is vital with regard to energy source sustainability, social and economic profitability and which can reduce air pollution and combat adverse impact of climatic change.

Finally, it is important to emphasize the point that a potentially sustainable model for off-grid PV diffusion would encompass community focused system design and community ownership and support models. Therefore, it can be said that the CRED model could in fact be used as a template to help other communities with similar needs to achieve the basic energy service of lighting and other associated needs enhanced by the provision of solar power in a more sustainable way. However, all the weakness of the model such as maintenance reporting procedures, warranties, business models for generation adequate funds for maintenance of the solar PV system etc should be reconsidered for design before replication.

5.6 Summary of Contributions

In essence, there is no other published literature providing evidence that shows social-economic and technical analysis of the outdoor solar PV systems in Malawi. Having studied the solar PV system through the CRED model and the author's own involvements in the CRED project, the following are the contributions this research study has achieved:

- Community based model proposed, tested and refined taking into account community input to all stages of solar PV sustainability.

- Establishment of a solar PV system community energy socio-economic and technical data bank which is critical for solar PV technology management. That is, accurate recording of income generation activities, system usage by various groups, system technical details (i.e. Wp, battey size, loads) and solar PV system performance data. The databank is being maintained on a monthly basis. Analysis of this data produced several original conclusions as set out above.
- Established that a sound PV system design, installation and operation for dc lighting and battery charging installed with Monocrystalline panel technology operates with high module efficiency of more than 12.84 % in the month of October in Chikhwawa district located in southern region of Malawi.
- The case study has indicated for long term sustainability of solar PV system the battery is a critical component in the solar PV systems. Therefore, sound asset management principles should be adopted such as the battery bank being charged/discharged between two voltage operating limits. For lead acid batteries used in this research work, it has been found out that a battery must not be charged for more than 13.7V or discharged for less than 11.8V for the areas under study. The author concludes that since the weather pattern in Malawi is fairly homogenous, then the voltage setting for the solar lead acid batteries for the charge and discharge cycle can be applicable for many areas as well.

5.7 Recommendations

Having looked at the CRED project's outcomes, the following recommendations have been proposed:

- Since community energy socio-economic and technical solar PV data is almost non-existent, there is need for the government to establish a data bank for all successful and unsuccessful community energy projects that include solar PV, micro hydro, biogas, efficient cooking stoves, wind etc. The data bank will be used to assist future planning and decision making around solar PV system projects as well as improve existing projects through the lessons learnt for successful project implementation or community energy trials.
- To ensure long sustainability of the solar PV system, the government must not only come up with solar PV installation standards but must enforce them through Malawi Bureau of Standards in conjunction with the Department of Energy. Such standards should

comprehensively look at all durability of solar PV components, sound system configurations and certified installers among others.

- Since solar PV systems are located in the remote rural areas where access is usually very difficult, there is need for the government to establish an effective maintenance model in order to achieve long term solar PV system sustainability.
- The government should take an initiative to come up with a solar radiation map the way it has already started drawing up a wind profile map for different locations in Malawi. The radiation map will assist the government to have an informed choice of the type of solar PV design a particular location should have in order to achieve the best performance. The radiation map can also act as guide to the government in choosing the best energy technology of the location in question.
- There should be proactive participation by the private sector to harness a wealth of renewable energy resources such as solar, wind energy etc adjusted to Malawian specific needs to cover local electricity demand. This will result in job creation and increased standard of living. There is anecdotal evidence that in developing countries, all renewable energy industry started up with small but reliable units increasing scale with time. To guarantee sustainable development the same process should be carried out in Malawi and the rest of Sub Saharan African countries.
- Reliability of community based off grid energy systems requires monitoring and control. Therefore, any technical breakdown should be reported urgently and corrective measures should be done with minimum delay. One way to do this is to deploy remote monitoring systems to inform operators in the community as well as the installer about system status. This would assist the community operators or maintenance team to know that the system is on breakdown and could facilitate quick measures to restore the system.

5.8 Further Work

As a complement to the results and conclusions highlighted in this thesis, the study also suggests that there are areas of research that need to be undertaken as indicated:

- Performance analysis for inverter, battery bank and load demand side management of solar PV systems in Malawi.
- Research is needed to help develop a business model that is appropriate for technology long term sustainability. That is, to identify potential income generation and enterprise opportunities that will significantly add value to socio-economic growth of the rural population.

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APPENDICES

Escom in massive blackouts

By **Watipaso Mzungu Jnr**

ELECTRICITY Supply Corporation of Malawi (Escom) is set to frustrate government's efforts to stop the production and sale of charcoal as it launches a six-month "extensive load shedding" this Friday.

The development is likely to leave consumers with no option but turn to charcoal and firewood for their kitchen uses.

Minister of Natural Resources, Energy and the Environment Grain Malunga is on record to have appealed to law enforcement authorities to arrest and jail all unlicensed charcoal vendors, who he also accuses of contributing significantly to the environmental degradation in the country.

Malunga argues that Malawi is losing a big percentage of forest reserve per year due to increases in population, poverty, agricultural expansion, woodfuel demands, market and policy failures, structural adjustment programmes, and forest fires.

To this effect, the minister has been imploring Malawians to replace charcoal with gas or electricity for their cooking needs as a measure to save the remaining forests from further depletion.

Whether people were willing to comply or not, will no longer be an issue now with the "six-month extensive load shedding" exercise Escom is scheduled to roll out (if not already launched) on July 8, which will run until December 31, 2011.

Escom spokesperson Kitty Chingota confirmed of the development, saying this has come about as a result of the increase in power demand "during winter period".

Chingota said during winter season (from May to August), Escom faces challenges to supply "power all day, everyday" to its consumers because there is generally an increase in demand against available supply.

CHARCOAL—Its demand will now increase

consumers want to use electricity on heavy electrical appliances such as geysers and heaters, which consume a lot of elelctricity against the supply. Thus, we're forced to increase duration of load shedding to safeguard our power supply system," she said, adding that Escom was also trying to balance between demand and supply.

"If the demand is higher than supply and we don't load shed, there'll be total collapse of the power supply system, which will result in a national blackout and a damage of the system."

As of Friday, Escom was able to generate a total of 266 megawatts against a demand of 310 megawatts, according to the publicist.

"Presently, we've a shortfall of

we're load shedding 20 megawatts only, but we're forced to increase due to the rise in the shortfall," said Chingota.

She, however, allayed fears consumers had that Escom was going to implement a six-hour continuous load shedding.

Chingota said the cumulative hours of load shedding will depend on available capacity against the demand in a day.

"Consumers will experience blackouts in the morning, midday and evening during peak hours. In some instances, the blackouts will take 12 hours, but not continuously. We'd like to request our customers to use electricity sparingly and switch off heavy electrical appliances during these periods for

load shedding," she pleaded.

In reaction to the development, Projects Officer for Consumers Association of Malawi (Cama) David Ngomba predicted that the extensive blackouts will have a negative impact on the general socioeconomic standing of the people, especially those in urban areas.

Ngomba noted that it was not Escom consumers that will suffer the consequences as many other urban settlers indirectly depend on electricity for their survival.

"We've residents living in houses without electricity, but earn their living through selling of freezes, which they order from people living in electrified houses. This means that their livelihoods will be negatively affected," he explained.

Ngomba wondered if Escom had the welfare of the people before coming up with the decision.

Malawi Confederation of Chamber of Commerce and Industry (MCCCI) chief executive officer Chancellor Kaferapanjira could not be reached for a comment as he was reportedly in a meeting when contacted for his views on the development.

But some entrepreneurs trading in freezes, thobwa (sweet beer/gruel) and sausages interviewed in Blantyre also feared their businesses will go down with the blackouts.

The manufacturing industry is also likely to be forced into scaling down production, a development that will reduce their annual revenues and subsequently tax remission thereby impacting on the zero deficit budget government has

Appendix 1: ESCOM Extensive Loading Shedding Programme. Implementation of an extensive load shedding programme because of an expected shut down at Tedzani power station and Nkula B machines which will be undergoing repairs up to end December this year. This will result in taking out 40 and 20 Megawatts at Tedzani and Nkula respectively. It is also planned that after December 2011, the load shedding programme will still continue due to the overhaul maintenance of the Nkula machines through a Millennium Challenge Cooperation funded project.

File view options ?

data | parameter

779 sets	I in	I out	I total	I mod	SOC	U	status	mV
24.10.10 01:22	0.0	0.8	-0.7	0.0	98	22.70	N	0.0
24.10.10 03:13	0.0	0.8	-0.8	0.0	96	20.82	N	0.0
24.10.10 05:05	0.0	0.8	-0.9	0.0	93	20.18	N	0.0
24.10.10 06:56	0.0	0.9	-0.9	0.0	90	19.45	N	0.0
24.10.10 08:47	0.0	1.0	-1.0	0.0	87	18.82	N	0.0
24.10.10 10:38	1.2	1.0	0.2	1.2	84	18.73	N	0.0
24.10.10 12:30	13.7	1.0	12.8	13.7	83	24.45		0.0
24.10.10 14:21	29.1	0.7	28.3	29.3	84	28.04		0.0
24.10.10 16:12	5.9	0.8	5.1	23.2	89	32.88		0.0
24.10.10 18:04	7.0	0.7	6.2	30.6	93	30.43		0.0
24.10.10 19:57	5.0	0.7	4.2	17.1	96	30.23		0.0
24.10.10 21:49	0.5	0.6	-0.3	0.6	98	28.36		0.0
24.10.10 23:40	0.0	0.8	-0.8	0.0	99	24.34	N	0.0
25.10.10 01:32	0.0	0.9	-0.9	0.0	97	21.84	N	0.0
25.10.10 03:23	0.0	0.9	-0.9	0.0	95	20.72	N	0.0
25.10.10 05:14	0.0	0.9	-1.0	0.0	92	20.07	N	0.0
25.10.10 07:05	0.0	0.9	-1.0	0.0	89	19.39	N	0.0
25.10.10 08:56	0.0	1.0	-1.0	0.0	86	18.77	N	0.0

read logger

☑ logging time automatic

22/08/2011 15:57:21

Appendix 2: Typical Summer Day Charge Controller solar PV performance data – 24/10/2010. The data is showing battery bank voltage response to solar radiation. The voltages at night (N) are lower than during the day.

Micro Circuit Labs SDL-1 Solar Data Logger

www.microcircuitlabs.com

Instructions

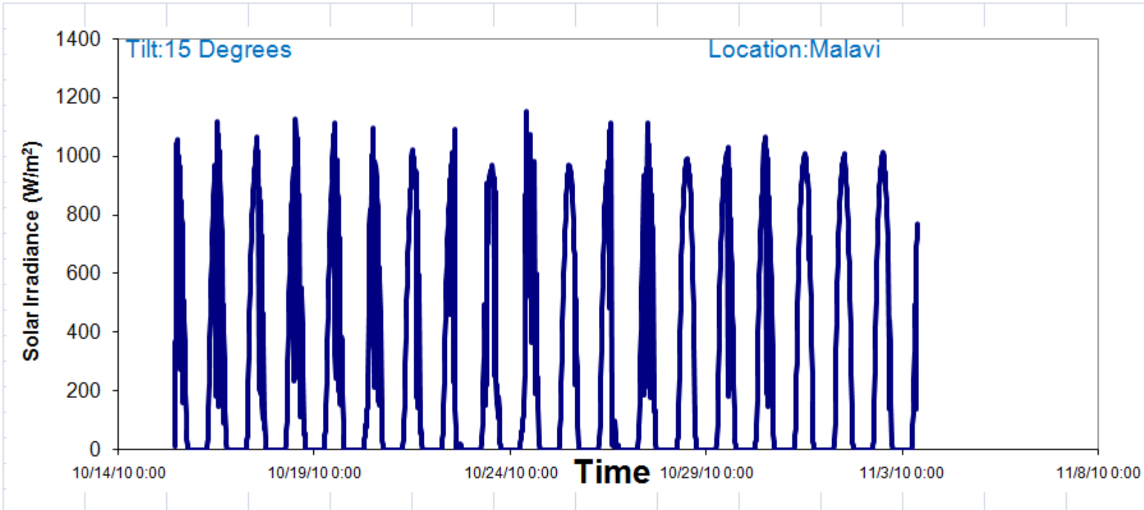
Step 1. Paste the raw SDL-1 data (including header) starting at cell B12 below.
Step 2. Enter start date and time in cell F12.
Step 3. Scroll to the right to view a plot of the data.

9.159	Initial VBATT (Volts)	
9.11	Final VBATT (Volts)	
122.98	Cumulative Solar Energy (kWh/m^2)	
900	Logging Interval (seconds)	

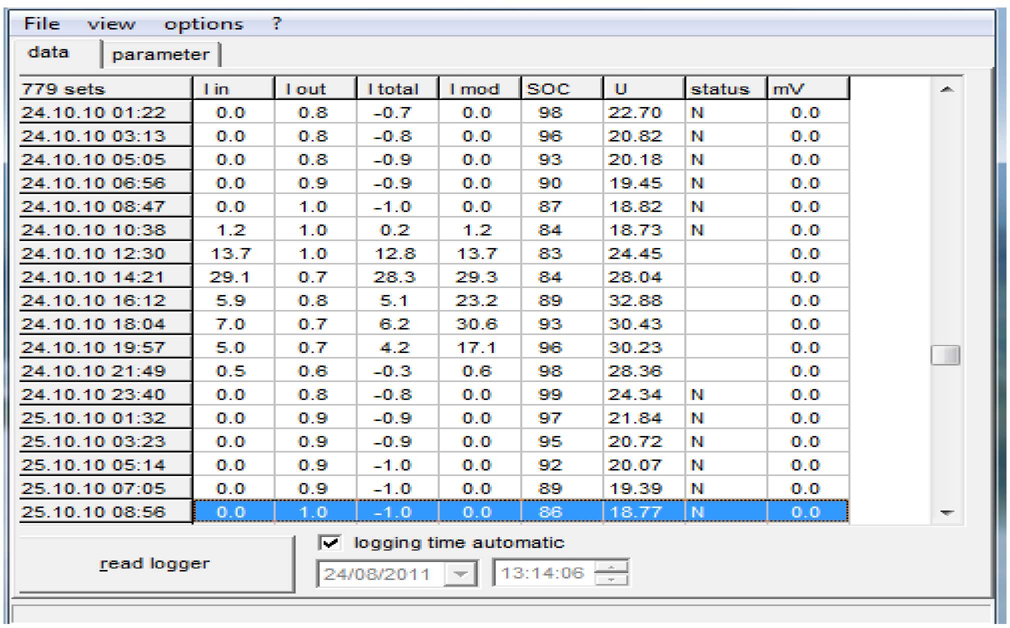
Enter Start Time: 20/10/2010 10:30
End Time: 08/11/2010 09:30
Total Energy (kWh/m2): 122.057

Sample Index	Reading Type 10x [Irradiance (W/m^2)]	**Time (day)**	**Solar Irradiance (W/m2)**
0	137	10/20/10 10:30	13.7
1	3705	10/20/10 10:45	370.5
2	3257	10/20/10 11:00	325.7
3	10461	10/20/10 11:15	1046.1
4	3412	10/20/10 11:30	341.2
5	10582	10/20/10 11:45	1058.2
6	9720	10/20/10 12:00	972.0
7	8479	10/20/10 12:15	847.9

Appendix 3: Typical Radiation Data in the Month of October 2010. The photodiode that measures the intensity of solar radiation is good detector of sunlight because its range of spectral sensitivity is from 400nm to 1100nm and overlaps the solar radiation spectrum from 300nm to 1800nm



Appendix 4: Typical solar intensity characteristics curve for Summer Month of October 2010. The SDL-1 Data logger helps to accurately measure the solar radiation for precise indication of the panel's performance.



779 sets	I in	I out	I total	I mod	SOC	U	status	mV
24.10.10 01:22	0.0	0.8	-0.7	0.0	98	22.70	N	0.0
24.10.10 03:13	0.0	0.8	-0.8	0.0	96	20.82	N	0.0
24.10.10 05:05	0.0	0.8	-0.9	0.0	93	20.18	N	0.0
24.10.10 06:56	0.0	0.9	-0.9	0.0	90	19.45	N	0.0
24.10.10 08:47	0.0	1.0	-1.0	0.0	87	18.82	N	0.0
24.10.10 10:38	1.2	1.0	0.2	1.2	84	18.73	N	0.0
24.10.10 12:30	13.7	1.0	12.8	13.7	83	24.45		0.0
24.10.10 14:21	29.1	0.7	28.3	29.3	84	28.04		0.0
24.10.10 16:12	5.9	0.8	5.1	23.2	89	32.88		0.0
24.10.10 18:04	7.0	0.7	6.2	30.6	93	30.43		0.0
24.10.10 19:57	5.0	0.7	4.2	17.1	96	30.23		0.0
24.10.10 21:49	0.5	0.6	-0.3	0.6	98	28.36		0.0
24.10.10 23:40	0.0	0.8	-0.8	0.0	99	24.34	N	0.0
25.10.10 01:32	0.0	0.9	-0.9	0.0	97	21.84	N	0.0
25.10.10 03:23	0.0	0.9	-0.9	0.0	95	20.72	N	0.0
25.10.10 05:14	0.0	0.9	-1.0	0.0	92	20.07	N	0.0
25.10.10 07:05	0.0	0.9	-1.0	0.0	89	19.39	N	0.0
25.10.10 08:56	0.0	1.0	-1.0	0.0	86	18.77	N	0.0

Appendix 5: Typical Data from Tarcom Data Logger for the System Manager. All the collected data from the logger is displayed in a table. These data sets can be stored to a file, exported to an Excel sheet or visualized in a chart.

Appendix 6: CRED technicians taking centre stage in the installation of solar PV system. A successful project will always include appropriate O & M in the design of the project.

Appendix 7: Students welcome solar lighting at Chilongoma Primary School in the remote rural area of Malawi. Successful projects are focused on meeting the basic necessities of the rural population to improve their quality of life i.e. lighting, small income generation, entertainment etc.

Appendix 8: A Local Chief giving goods to less privileged in the village community. The goods included food stuff, clothes and educational materials were bought from funds realized through CRED income generating activities. A successful project will always encourage and motivate the local population for it to remain sustainable.