

**STUDY OF THE MAJOR SOLAR ENERGY MINI-GRIDS
INITIATIVES IN ZAMBIA**

**BY;
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Declaration

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Signature.....

Date.....

Dedication

This dissertation is dedicated to my mother (Laika Mutinta Muzambalika) and my late daddy (Peter Kapole) for their never-failing support and sacrifice towards my education. They were always there for me whenever I needed them.

Abstract

The Solar mini-grid initiatives aim to provide access to electricity to rural and remote areas which are currently not connected to the national grid. However, the implementation of solar mini-grids in Zambia presents challenges and therefore understanding the success factors and challenges of these factors is crucial to ensure their sustainability and scalability. There is very little study conducted to assess their status, impact on Zambia's energy security, financial viability and environmental sustainability. There is also no coherent single document for the information on solar mini grids in Zambia. To address this gap, this research provides a critical study of financial, technical, environmental and social sustainability of five major solar energy mini-grid initiatives in Zambia, Viz 48 kW Magodi mini-grid in Lundazi, 51.8 kW Katamanda mini-grid in Chipangali, 28.35 kW Chitandika mini-grid in Chipangali, 24.4 kW Sinda mini-grid in Sinda (all in the Eastern Province of Zambia) and 32.4 kW Chibwika mini-grid in Mwinilunga in the North Western Province of Zambia. None of the five solar mini-grids is fully sustainable financially and technically. Economic tariffs that can sustain both capital and operational expense are mostly unaffordable to the rural people due to their low-income levels. Challenges of lack of technical support, poor operations and maintenance are also major cause of unsustainability. All solar mini grids are running on an ad-hoc and/or pilot basis without a well thought out plan of operations and business model. The specific challenges facing the Zambian mini grids include (i) incorrect sizing of the mini grids during planning stage, (ii) inefficient operation of the mini grid by government agency or the community without adequate technical support, (iii) wastage of subsidies being provided to private sector without aligning it with diverse interests and expectations, (iv) ad-hoc and inappropriately structured tariff plans. For both technical and financial efficiency, involvement of private sector is cardinal. A well thought out public private partnership model for the construction, operation and maintenance of the solar mini grids is needed. In place of an up-front subsidy as being given currently, smart subsidies which should align the interests and expectations of the government, the private sector and the clients should be developed.

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Table of Contents

| | |
|---------------------------------------|------|
| Copyright Declaration | i |
| Declaration..... | ii |
| Dedication | iii |
| Approval..... | iv |
| Abstract..... | v |
| Acknowledgements..... | vi |
| Table of Contents..... | vii |
| List of Tables | xiii |
| List of Figures | xv |
| Acronyms | xvi |
| CHAPTER 1..... | 1 |
| 1.0 INTRODUCTION | 1 |
| 1.1 Background of the study..... | 1 |
| 1.2 Statement of the Problem | 1 |
| 1.3 Aim | 1 |
| 1.4 Objectives..... | 1 |
| 1.5 Research Questions | 2 |
| 1.6 Significance of the Study..... | 3 |
| 1.7 Study Area | 3 |
| 1.7.1 Chibwika solar mini-grid | 3 |
| 1.7.2 Chitandika solar mini-grid..... | 3 |
| 1.7.3 Katamanda solar mini-grid..... | 4 |
| 1.7.4 Magodi solar mini-grid..... | 4 |
| 1.7.5 Sinda solar mini-grid | 5 |

| | |
|---|----|
| 1.8 Scope and Limitation of the Study | 5 |
| CHAPTER 2..... | 6 |
| 2.0 REVIEW OF LITERATURE..... | 6 |
| 2.1 Solar mini-grids in Zambia..... | 6 |
| 2.2 Solar energy | 6 |
| 2.3 Solar Radiation and Solar Energy Cycle | 7 |
| 2.4 Solar PV System | 8 |
| 2.4.1 PV system components..... | 8 |
| 2.4.1.1 Solar panel | 8 |
| 2.4.1.2 Inverters | 8 |
| 2.4.1.3 Charge controller | 9 |
| 2.4.1.4 Solar batteries..... | 10 |
| 2.4.1.5 Racking | 10 |
| 2.4.1.6 Other components | 11 |
| 2.4.2 PV system operation | 11 |
| 2.5 Types of PV Grids | 11 |
| 2.5.1 Off-grid solar PV system | 12 |
| 2.5.2 Solar mini-grid PV system | 12 |
| 2.5.3 Utility scale or grid-connected solar PV system | 13 |
| 2.5.4 Hybrid systems..... | 13 |
| CHAPTER 3..... | 14 |
| 3.0 RESEARCH METHODOLOGY AND MATERIALS..... | 14 |
| 3.1 Overview | 14 |
| 3.1.1 Research design | 14 |
| 3.1.2 Study area | 14 |
| 3.1.3 Study population..... | 15 |
| 3.1.4 Sample size..... | 15 |
| 3.1.5 Data collection method | 15 |
| 3.1.6 Primary Data | 16 |
| 3.1.7 Secondary data | 16 |
| 3.2 Data Analysis..... | 16 |

| | |
|---|----|
| 3.3 Dimension of sustainability of studied solar mini-grids | 17 |
| 3.3.1 Technical sustainability | 17 |
| 3.3.2. Economic sustainability | 17 |
| 3.3.3 Environmental sustainability | 17 |
| 3.3.4 Social sustainability..... | 18 |
| 3.4 Ethical Consideration | 18 |
| CHAPTER 4..... | 19 |
| 4.0 RESULTS AND DATA ANALYSIS | 19 |
| 4.1 Chibwika solar mini-grid | 19 |
| 4.1.1 Economic sustainability | 19 |
| 4.1.1.1 Funding and cost of the plant..... | 20 |
| 4.1.1.2 Tariff structure and business model..... | 20 |
| 4.1.1.3 Socio economic profile (occupation, average yearly income, income spread, willingness to pay for electricity, and typical expenditure)..... | 20 |
| 4.1.1.4 Sustainability assessment..... | 23 |
| 4.1.1.4.1 Monthly and yearly revenues | 23 |
| 4.1.1.4.2 Operational costs and salaries for workers | 23 |
| 4.1.1.4.3 Sustainable tariff estimation..... | 26 |
| 4.1.2 Technical sustainability (configuration and specifications)..... | 27 |
| 4.1.2.1 Solar PV modules | 27 |
| 4.1.2.2 Batteries | 28 |
| 4.1.2.3 Inverters, charge controllers and backup diesel generator..... | 29 |
| 4.1.3 Daily energy load in comparison with system size | 30 |
| 4.1.4 Challenges | 31 |
| 4.1.5 Remedies..... | 31 |
| 4.2 Chitandika solar mini-grid..... | 32 |
| 4.2.1 Economic sustainability | 32 |
| 4.2.1.1 Funding and cost of the plant..... | 32 |
| 4.2.1.2 Tariff structure and business model..... | 33 |
| 4.2.1.3 Socio economic profile (occupation, average yearly income, income spread and typical expenditure) | 33 |
| 4.2.1.4 Sustainability assessment..... | 35 |

| | |
|--|----|
| 4.2.1.4.1 Monthly and yearly revenues | 36 |
| 4.2.1.4.2: Sustainable tariff estimation | 37 |
| 4.2.2 Technical sustainability (configuration and specifications)..... | 38 |
| 4.2.2.1. Solar PV modules | 38 |
| 4.2.2.2 Batteries | 38 |
| 4.2.2.3 Inverters and charge controllers..... | 39 |
| 4.2.3 Daily energy load in comparison with system size | 40 |
| 4.2.4 Challenges | 40 |
| 4.2.5 Remedies..... | 41 |
| 4.3 Katamanda solar mini-grid..... | 41 |
| 4.3.1 Economic sustainability | 42 |
| 4.3.1.1 Funding and cost of the plant..... | 42 |
| 4.3.1.2 Tariff structure and business model..... | 42 |
| 4.3.1.3 Socio economic profile (Occupation, average yearly income, income spread, willingness to pay for electricity, and typical expenditure)..... | 42 |
| 4.3.1.4 Sustainability assessment..... | 44 |
| 4.3.1.4.1 Monthly and Yearly revenues..... | 44 |
| 4.3.1.4.2 Operational costs..... | 45 |
| 4.3.1.4.3 Sustainable tariff estimation..... | 45 |
| 4.3.2 Technical sustainability (configuration and specifications)..... | 46 |
| 4.3.2.1 Solar PV modules | 46 |
| 4.3.2.2 Batteries | 47 |
| 4.3.2.3 Inverters and charge controllers..... | 47 |
| 4.3.3 Daily energy load in comparison with system size | 48 |
| 4.3.4 Challenges | 48 |
| 4.3.5 Remedies..... | 48 |
| 4.4 Magodi solar mini-grid..... | 49 |
| 4.4.1 Economic sustainability | 49 |
| 4.4.1.1 Funding and cost of the plant..... | 49 |
| 4.4.1.2 Tariff structure and business model..... | 50 |
| 4.4.1.3: Socio economic profile (occupation, average yearly income, income spread, willingness to pay for electricity, and typical expenditure)..... | 50 |

| | |
|--|----|
| 4.4.1.4 Sustainability assessment..... | 52 |
| 4.4.1.4.1 Monthly and Yearly revenues..... | 52 |
| 4.3.1.4.2 Operational costs..... | 52 |
| 4.4.1.4.3 Sustainable tariff estimation..... | 52 |
| 4.4.2 Technical sustainability (configuration and specifications)..... | 53 |
| 4.4.2.1 Solar PV modules | 53 |
| 4.4.2.2 Batteries | 54 |
| 4.4.2.3 Inverters and charge controllers..... | 55 |
| 4.4.3 Daily energy load in comparison with system size | 55 |
| 4.4.4 Challenges | 56 |
| 4.4.5 Remedies..... | 56 |
| 4.5 Sinda solar mini-grid | 56 |
| 4.5.1 Economic Sustainability | 57 |
| 4.5.1.1 Funding and cost of the plant..... | 57 |
| 4.5.1.2 Tariff structure and business model..... | 57 |
| 4.4.1.3 Socio economic profile (occupation, average yearly income, income spread, willingness to pay for electricity, and typical expenditure) | 58 |
| 4.5.1.4 Sustainability assessment..... | 60 |
| 4.5.1.4.1 Monthly and yearly revenues | 60 |
| 4.5.1.4.2 Operational costs..... | 61 |
| 4.5.1.4.3 Sustainable tariff estimation..... | 61 |
| 4.5.2 Technical sustainability (configuration and specifications)..... | 62 |
| 4.5.2.1 Solar PV modules | 62 |
| 4.5.2.2 Batteries | 63 |
| 4.5.2.3 Inverters and Charge controllers..... | 63 |
| 4.5.3 Daily energy load in comparison with system size | 64 |
| 4.5.4 Challenges | 65 |
| 4.5.5 Remedies..... | 65 |
| CHAPTER 5..... | 66 |
| 5.0 DISCUSSION..... | 66 |
| 5.1 Social sustainability..... | 66 |

| | |
|---|----|
| 5.2 Environmental sustainability | 67 |
| 5.3 Tariff structure and analysis for the five (5) solar mini-grids | 69 |
| 5.4 Overall sustainability..... | 72 |
| CHAPTER 6..... | 73 |
| 6.0 CONCLUSION, COMMON CHALLENGES AND RECOMMENDATIONS..... | 73 |
| 6.1 Conclusion..... | 73 |
| 6.2 Common challenges..... | 75 |
| 6.3 Recommendations | 77 |
| 6.4 Recommendation for further studies | 78 |
| REFERENCES | 79 |
| APPENDICES | 85 |
| Appendix 1 | 85 |
| Appendix 2 | 91 |
| Appendix 3 | 92 |
| Appendix 4 | 96 |

List of Tables

| | |
|---|----|
| Table 1: Occupation of Chibwika residents..... | 21 |
| Table 2: Family’s typical expenditure for Chibwika residents..... | 22 |
| Table 3: Price of Solar components and their specification | 24 |
| Table 4: Estimated total replacement and annual maintenance cost..... | 25 |
| Table 5: Estimated overhead costs for the five (5) SMGs | 25 |
| Table 6: Annual energy generated and tariff estimation for Chibwika SMG..... | 26 |
| Table 7:Chibwika Solar PV module specification..... | 27 |
| Table 8: Chibwika solar PV module configuration | 28 |
| Table 9: Battery specification & configuration | 29 |
| Table 10: Inverter Specification & Configuration of Chibwika SMG | 30 |
| Table 11: Charge controller type and configuration of Chibwika SMG | 30 |
| Table 12: Energy consumption of Chibwika residents..... | 31 |
| Table 13: Distribution of respondents by occupation..... | 33 |
| Table 14: Typical expenditure for family of Chitandika residents..... | 35 |
| Table 15: Monthly and yearly revenues of Chitandika solar mini-grid..... | 36 |
| Table 16: Estimated annual maintenance cost for Chitandika SMG | 36 |
| Table 17: Annual energy generated and tariff estimation for Chitandika | 37 |
| Table 18: Chitandika Solar PV modules specification | 38 |
| Table 19: Chitandika Solar PV configuration..... | 38 |
| Table 20: Battery Specification & configuration..... | 39 |
| Table 21: Inverter specification | 39 |
| Table 22: Charge controller type and specifications..... | 39 |
| Table 23: Energy consumption of Chitandika residents | 40 |
| Table 24: Distribution of Respondents by Occupation for Katamanda..... | 42 |
| Table 25: Katamanda residents typical family expenditure..... | 44 |
| Table 26: Estimated annual maintenance cost for Katamanda SMG | 45 |
| Table 27: Annual energy generated and tariff estimation for Katamanda SMG | 46 |
| Table 28: Katamanda Solar PV module specification | 46 |
| Table 29: Katamanda Solar PV module configuration | 47 |
| Table 30: Battery specification & configuration | 47 |
| Table 31: Katamanda solar mini grid daily energy consumption table | 48 |
| Table 32: Magodi distribution of respondents by occupation | 50 |
| Table 33: Typical family expenditure for Magodi residents | 51 |
| Table 34: Estimated annual maintenance cost for Magodi SMG | 52 |
| Table 35: Annual energy generated and tariff estimation for Magodi SMG..... | 53 |
| Table 36: Magodi Solar PV module specification..... | 54 |
| Table 37: Magodi Solar PV module configuration..... | 54 |
| Table 38: Magodi Battery Specification & configuration | 54 |

| | |
|--|----|
| Table 39:Magodi SMG inverter specification | 55 |
| Table 40: Magodi SMG charge controller specifications | 55 |
| Table 41: Magodi solar mini grid daily energy consumption table | 56 |
| Table 42: Sinda distribution of respondents by occupation..... | 58 |
| Table 43: Sinda resident’s typical family expenditure | 59 |
| Table 44: Estimated annual maintenance cost for Sinda SMG..... | 61 |
| Table 45: Annual energy generated and tariff estimation for Sinda SMG | 62 |
| Table 46: Sinda solar PV module specification | 62 |
| Table 47: Sinda solar PV module configuration..... | 63 |
| Table 48: Sinda SMG battery specification & configuration | 63 |
| Table 49: Sinda SMG inverter specification..... | 64 |
| Table 50: Sinda SMG charge controller specifications | 64 |
| Table 51: Sinda solar mini-grid daily energy consumption table | 65 |
| Table 52: Sources of energy for lighting before implementation of solar mini-grids | 67 |
| Table 53: Sources of energy for lighting after implementation of solar mini grids | 68 |
| Table 54: Annual revenue and total annual cost of the SMGs | 70 |
| Table 55: Economic sustainability of the five (5) solar mini-grids | 71 |
| Table 56: Overall sustainability of the five (5) solar mini-grids | 72 |

List of Figures

| | |
|--|----|
| Figure 1: Katamanda Solar Mini-Grid Battery bank | 10 |
| Figure 2: Chitandika solar mini-grid system | 12 |
| Figure 3: Chibwika solar mini-grid..... | 19 |
| Figure 4: Average yearly income for chibwika SMG..... | 21 |
| Figure 5: Income spread for Chibwika residents | 22 |
| Figure 6: willingness to pay for electricity per month of Chibwika residents..... | 23 |
| Figure 7 : Chitandika solar mini-grid..... | 32 |
| Figure 8: Average yearly income for Chitandika residents | 34 |
| Figure 9 :Income spread for Chitandika residents | 34 |
| Figure 10: Payment bands of Chitandika residents..... | 35 |
| Figure 11 Katamanda solar mini-grid PV configuration | 41 |
| Figure 12: Average yearly income for Katamanda residents..... | 43 |
| Figure 13: Income spread for Katamanda residents | 43 |
| Figure 14: Payment band of Katamanda residents | 44 |
| Figure 15: Magodi solar mini-grid..... | 49 |
| Figure 16: Average yearly income for Magodi residents | 50 |
| Figure 17: Income spread for Magodi residents | 51 |
| Figure 18: Amount of money Magodi residents were willing to pay for electricity per month .. | 51 |
| Figure 19: Sinda solar mini-grid | 57 |
| Figure 20: Average yearly income of Sinda residents | 58 |
| Figure 21: Income spread for Sinda residents..... | 59 |
| Figure 22: Amount of money Sinda residents were willing to pay for electricity per month | 60 |

Acronyms

| | |
|-----------------|--------------------------------------|
| AC | Alternating Current |
| AFR | African Energy Resources |
| AGM | Absorbed Glass Mat |
| Ah | Ampere-hour |
| ARE | Alliance for Rural Electrification |
| BOS | Balance of System |
| CAPEX | Capital Expenditure |
| °C | Degree Celsius |
| CO ₂ | Carbon dioxide |
| DC | Direct Current |
| DNI | Direct Normal Irradiation/Irradiance |
| DoD | Depth of Discharge |
| EG | Energy generated |
| EJ | Exajoules |
| EPA | Environmental Protection Agency |
| EUR | Euro |
| ERB | Energy Regulation Board |
| GCP | Global Carbon Project |
| GHGs | Greenhouse gasses |
| GHI | Global Horizontal Irradiance |
| GPS | Global Positioning System |

| | |
|------------|---|
| HHs | Households |
| HPS | Hybrid Power System |
| HRES | Hybrid Renewable Energy System |
| IEA | International Energy Agency |
| K | Kelvin |
| Kg | Kilogram |
| kVA | Kilovolt-ampere |
| kW | Kilowatt |
| kWp | Kilowatt Peak |
| kWh | Kilowatt-hour |
| KIIs | Key Informant Interviews |
| Li | Lithium |
| MoE | Ministry of Energy |
| MPPT | Maximum Power Point Tracking |
| MW | Megawatt |
| NASA | National Aeronautics and Space Administration |
| NTBC | National Technology Business Centre |
| O & M | Operation and Maintenance |
| OPEX | Operational Expenditure |
| PDF | Portable Document Format |
| P_{\max} | Maximum power |
| PPA | Power Purchase Agreement |
| PT | Power Tracker |

| | |
|-------|---|
| PV | Photovoltaic |
| PW | Petawatts |
| PWM | Pulse Width Modulation |
| RCZ | Reformed Church of Zambia |
| REA | Rural Electrification Authority |
| RHC | Rural Health Centre |
| SPSS | Statistical Package for the Social Sciences |
| SUV | Solar Ultraviolet |
| TVs | Televisions |
| UN | United Nations |
| UNDP | United Nations Development Programme |
| UNZA | University of Zambia |
| UPS | Uninterrupted Power Supply |
| USA | United States of America |
| USADF | United States African Development Foundation |
| USD | United States Dollar |
| Wp | Watt peak |
| ZABS | Zambia Bureau of Standards |
| ZMW | Zambian Kwacha |
| ZESCO | Zambia Electricity Supply Corporation Limited |

CHAPTER 1

1.0 INTRODUCTION

1.1 Background of the study

In recent years, population increase and industrialization have resulted in an increasing burning of fossil fuels, deforestation, and develop most of land for farms, cities, and roads. These activities have contributed to climate change [1]. Zambia like many other Sub-Saharan African regions is facing a severe power crisis due to increasing unreliable rainfall patterns leading to prolonged droughts over the past two decades, which in turn has paralyzed the country's power sector due to its dependence on hydropower. The situation has led to an acute shortage of electricity, forcing the country to rely on expensive fossil fuel-based generation such as the use of generators to produce electricity [2]. As a clean source of energy, Zambia has realized the need to diversify its energy sources to solar which can be harnessed through solar mini-grids, off-grids and on-grids configuration. A solar mini-grid is a small scale electricity network fed by solar energy to supply a community [3].

1.2 Statement of the Problem

A number of solar energy mini-grids have come up recently in Zambia. Nevertheless, limited research has been conducted to assess their status and impact on Zambia's energy security, financial viability and environmental sustainability. This research gap is significant as it hinders the effective development and implementation of solar mini-grids in Zambia. To address this gap in the literature, this study intends to investigate the major solar energy mini-grid initiatives in Zambia [4].

1.3 Aim

The aim of this project is to assess the status and impact of the major solar energy mini-grid initiatives in Zambia.

1.4 Objectives

The study had five main objectives which were to;

- i. Update information and documentation about major initiatives in solar mini-grids in Zambia.
- ii. Evaluate the technical designs and configurations of the solar mini-grids, assess daily energy load requirements of the community and investigate solar mini-grids' suitability and optimality for the given community.
- iii. Analyze the strengths and weaknesses of operational and financial/tariff models in place for solar mini-grids and provide recommendations on how to improve the financial sustainability of the solar mini-grids.
- iv. Analyze the environmental impact of solar mini-grids on the community, and
- v. Generate recommendations for the development and scaling up of solar mini-grids in Zambia on early initiatives and their impact on Zambia's energy security, financial viability and environmental sustainability.

1.5 Research Questions

- i. How can we get comprehensive information about solar mini-grids in Zambia in one place?
- ii. What are the technical designs and configurations of the solar mini-grids and what are their impacts on energy security, financial viability, environmental sustainability and social acceptability, what are the daily energy load requirements of the community?
- iii. What are the strengths and weaknesses of the operational tariff models in place for solar mini-grids?
- iv. What are the environmental impacts of solar mini-grids on the community and Zambia at large?
- v. What are the recommendations from early initiatives and their impact on Zambia's energy security, financial viability and environmental sustainability?

In answering these questions, a case study was undertaken by visiting five (5) solar mini-grids in Zambia and information on the technical configuration, and daily energy load requirement of the community was collected and analyzed. Community questionnaires were prepared to find out experience of the consumers use of solar energy from which the financial viability and environmental sustainability of the solar mini grids were analyzed.

1.6 Significance of the Study

The study is useful to various stakeholders in the energy sector like the Ministry of Energy (MoE), Rural Electrification Authority (REA), Government bodies and solar energy players through proper documentation and detailed information on solar energy mini-grid initiatives. The Ministry of Energy (MoE) and Rural Electrification Authority (REA) could use the findings to inform policy decisions and investment strategies in the energy sector. Government bodies could use the study to assess the impact of solar mini-grids on rural development and poverty alleviation. Solar energy players could use the insights gained from the study to improve their business models and enhance their contribution to sustainable development.

1.7 Study Area

This study was conducted in five different communities across two provinces in Zambia. The communities chosen were Chibwika in Mwinilunga district of North Western province, as well as Chitandika, Magodi, Katamanda and Sinda in the Eastern Province. These communities were selected due to their varying geographical, economic and social characteristics, which provide a diverse range of contexts to the implementation and impact of solar mini-grids.

1.7.1 Chibwika solar mini-grid

Chibwika solar mini-grid is located at chief Chibwika Palace in Mwinilunga district of North Western province with GPS coordinates of 12° 40' South, 24° 29' East on an elevation of 1357 m above sea level. The area has a solar irradiance of 5.742 kWh/m²/day [5]. The system has a total capacity of **32.4 kWp** which translates to 186 kWh of energy generation per day. The plant was commissioned in 2019 and installed by a Chinese company Huawei though it is now run by the community, the plant is operational with an initial plan of supplying power to 300 households. However, by October 2020, only 108 households were connected.

1.7.2 Chitandika solar mini-grid

Chitandika solar mini-grid is located in Chipangali district of Eastern Province with GPS coordinates of 13° 19' South, 32° 38' East on an elevation of 983 m above sea level. The area has a solar irradiance

of 5.775 kWh/m²/day [5]. The system's total capacity is **28.35 kWp** which translates into 164 kWh of energy generation per day. The plant was commissioned in 2019 and run/installed by Engie Power Corner. The plant is operational and supplies power to a total number of 156 households and some commercial users during the period of proposed study.

1.7.3 Katamanda solar mini-grid

Katamanda solar mini-grid is located in Tamanda village, Chipangali district of eastern province with GPS coordinates of 13° 26' South, 32° 52' East on an elevation of 1089 meters above sea level. The area boasts of 5.786 kWh/m²/day solar irradiance [5]. The plant total capacity is **51.8 kWp** which translates to 300 kWh of energy generation per day. It was commissioned in 2017 and installed by ETERN company. The plant currently supplies power to a total number of 273 households, two schools and a Rural Health Centre. The SMGs can supply power to more than 400 households. The project managers also offered technical training to three electricians who were trained on how to electrify the needful institutions and households in the area. The three technicians were from Chipata council though currently they are no longer working at the station which takes the village headman of Tamanda to be the chairman of the solar mini grid.

1.7.4 Magodi solar mini-grid

Magodi solar mini-grid is located at chief Magodi's Palace in Chasefu district of Eastern Province with GPS coordinates of 11° 57'South, 33° 09' East on an elevation of 1163 m above sea level. The area receives 5.694 kWh/m²/day Solar irradiance [5]. The plant's total capacity is **48 kWp** which can generate a total energy of 273 kWh per day. The solar mini-grid was commissioned in 2017 and installed by NTBC. The number of households that could be connected to the SMG was estimated to be 240, but it reduced to 190 households. This was due to power supply faults developed due to the collapse of the storage equipment building of the SMG. Currently the grid is run and managed by NTBC, however, it is not operational due to some technical faults caused by lightning which resulted in the breakdown of the inverter. Furthermore, it was found that there was no training conducted in terms of technical assistance. The time the grid was in operation, it used to supply power to a nearby rural school and one (1) Rural Health Centre (RHC).

1.7.5 Sinda solar mini-grid

Sinda solar mini-grid is located in Sinda district of Eastern Province with GPS coordinates of 14° 15'South, 31° 40' East on an elevation of 1086 m above sea level. The area has a solar irradiance of 5.875 kWh/m²/day [5]. The system's total capacity is **24.40 kWp** which translates to 143 kWh of energy generation per day. The plant was commissioned in 2017 and run/installed by Muhanya Solar Company. The plant is operational even though the current number of households have reduced from the estimated 300 the plant could possibly supply from the installation of the plant.

1.8 Scope and Limitation of the Study

The study explored the role of solar mini-grids in rural electrification and their impact on the community livelihood within the selected areas. The villages were purposely selected because they were the beneficiaries of the solar mini-grid electricity. The limitations of this study were the reluctance of to provide relevant information, minimal understanding of the questions asked due to a lack of formal education, and the remote locations study areas. Additionally, there were financial constraints that limited the number of trips to visit more than five (5) SMGs in Zambia.

However, to mitigate these limitations, different solutions were taken such as; explaining what the study meant and informing community that confidentiality on every information given was to be maintained, and restructuring the questions when asking to make them easily understood by the respondents.

CHAPTER 2

2.0 REVIEW OF LITERATURE

2.1 Solar mini-grids in Zambia

A number of solar mini-grids have come up recently in Zambia, notably Mpanta in Luapula Province, Chitandika and Katamanda in the Eastern Province, Sinda in Sinda, Ngwerere in Lusaka, and Chibwika in North Western Province. There are more solar mini-grids on the cards including Moyo, Lunga and Chunga in Southern, Luapula and Central Provinces respectively. In addition, Standard Micro Grid have developed 12 solar mini-grids in Zambia, Solera an Egyptian Company have also developed 10 solar mini-grids in Zambia to be specific in the Eastern Province. So far solar mini grids are found to be financially unsustainable [6]. More work on technical optimization, social and economic issues needs to be done to make them more sustainable. Since 2006, the Rural Electrification Authority (REA) has implemented several rural electrification projects to supply electricity to communities in line with the government's vision of increasing electricity access to 51% by the year 2030. However, the rate of rural electrification is still very low e.g. 4.4% for grid power and 7.4% for solar power. In this vein mini-grids are often the only least cost option of electrifying rural communities [7].

2.2 Solar energy

Solar energy is light and heat radiated from the Sun. It is a clean source of energy that is harnessed using different technologies such as photovoltaics (converts sunlight into electricity) and solar thermal energy (heat from the Sun is used to make hot water or steam). It is also used in molten salt power plants and artificial photosynthesis [8].

Solar energy technologies are broadly characterized as either active solar or passive solar depending on how they capture and distribute solar energy or convert it into solar power. Active solar techniques include the use of photovoltaic systems, concentrated solar power, and solar water heating to harness the energy. On the other hand, passive solar techniques include orienting a building to the Sun, selecting materials with favorable thermal mass or light-dispersing properties, and designing spaces that naturally circulate air. Being available in a large size as well as cheaper compared to fossil fuels

as at now makes solar energy a highly appealing source of electricity [9]. The United Nations Development Programme (UNDP) in its 2000 World Energy Assessment found that the annual potential of solar energy was 1,575 to 49,837 exajoules (EJ) which is several times larger than the total world energy consumption of 560 EJ in the year 2012 [10].

According to the International Energy Agency (IEA), the development of affordable, inexhaustible and clean solar energy technologies will have huge longer-term benefits. It will increase the country's energy security through reliance on an indigenous, inexhaustible, and most importantly-independent resource. It will also enhance sustainability, reduce pollution, lower the costs of mitigating global warming, and keep fossil fuel prices lower than otherwise. These advantages are global as they will help us save the world and make it sustainable for human habitation. [10].

2.3 Solar Radiation and Solar Energy Cycle

Solar radiation is defined as a radiant energy emitted from the sun via a nuclear fusion reaction that creates electromagnetic energy. The spectrum of solar radiation is close to that of a black body with a temperature of about 5800 K. It is important to know that, the Earth receives about 174PW of incoming solar radiation (insolation) at the upper atmosphere [11]. However, approximately 31% of Solar radiation is reflected back to space while the rest is absorbed by clouds, oceans and land masses. The spectrum of solar light at the Earth's surface is mostly spread across the visible and near-infrared ranges with a small part in the near-ultraviolet [12]. Warm air containing evaporated water from the oceans rises, causing atmospheric circulation or convection. When air reaches a high altitude, where the temperature is low, water vapor condenses into clouds, which rain onto the Earth's surface, completing the water cycle. The latent heat of water condensation amplifies convection, producing atmospheric phenomena such as wind, cyclones and anticyclones [13]. Sunlight absorbed by the oceans and land masses keeps the surface at an average temperature of 14°C [14]. By photosynthesis, green plants convert solar energy into chemically stored energy, which produces food, wood and the biomass from which fossil fuels are derived [15].

The total solar energy absorbed by Earth's atmosphere, oceans and land masses is approximately 3,850,000 EJ per year [16]. This is more energy in one hour than the world used in one year as of the year 2002, implying that the amount of solar energy reaching the surface of the planet is so vast that in one year it is more than ever be obtained from all of the Earth's non-renewable resources of coal,

oil, natural gas, and mined uranium combined [17]. However, it is saddening that, despite all this vast amount of solar energy on earth, people still use a lot of fossil fuels which is highly environmental unfriendly.

2.4 Solar PV System

A Photovoltaic system also known as a PV system or solar power system, is a power system designed to supply usable solar power by means of photovoltaics. PV systems can vary greatly in size from small rooftop or portable systems to massive utility-scale generation plants [18].

2.4.1 PV system components

In addition to the solar panels, there are other important components of a photovoltaic system which are commonly referred to as the "Balance of System" (BOS) [19]. These include inverters, charge controllers, solar batteries, racking and other components.

2.4.1.1 Solar panel

A solar panel is a device that converts sunlight into electricity by using photovoltaic (PV) cells. These cells are made of materials (semiconductor) that generate electrons when exposed to light. On either side of the semiconductor is a layer of conducting material which collects the electricity produced. The electrons flow through a circuit and produce direct current (DC) electricity. The solar panel also consists of an illuminated side of the panel that contains an anti-reflection coating which minimize the losses due to reflection. The majority of solar panels produced worldwide are made from crystalline silicon, which has a theoretical efficiency limit of 33% for converting the Sun's energy into electricity. Many other semiconductor materials and solar cell technologies have been developed that operate at higher efficiencies, however these types are expensive [18].

2.4.1.2 Inverters

An inverter is an electrical device which converts direct current (DC) to alternating current (AC). For solar energy systems, this means the DC current from the solar array is fed through an inverter which converts it to AC. Most inverters have conversion efficiencies of 90% or higher and contain important safety features including ground fault circuit interruption and anti-islanding. These shut

down the PV system when there is a loss of grid power [19]. Solar inverters may be classified into different types which includes;

- i. Stand-alone inverters: These are used in isolated systems where the inverter draws its DC energy from batteries charged by photovoltaic arrays. Many stand-alone inverters also incorporate integral battery chargers to replenish the battery from an AC source, when available. Normally these do not interface in any way with the utility grid, and as such, are not required to have anti-islanding protection [20].
- ii. Grid-tie inverters: These devices convert direct current into alternating current and match phase with a utility-supplied sine wave. Grid-tie inverters are designed to shut down automatically upon loss of utility supply for safety purposes. They do not provide backup power during utility outages [20].
- iii. Battery backup inverters: These are special inverters which are designed to draw energy from a battery, manage the battery charge via an onboard charger, and export excess energy to the utility grid. These inverters are capable of supplying AC energy to selected loads during a utility outage, and are required to have anti-islanding protection [20].
- iv. Intelligent hybrid inverters: These inverters are a combination of a solar inverter and a battery inverter in a single piece of equipment that can intelligently manage power from solar panels, solar batteries, and the utility grid at the same time. These modern all-in-one systems are usually highly versatile and can be used for grid-tie, stand-alone or backup applications but their primary function is self-consumption with the use of storage [21].

2.4.1.3 Charge controller

A charge controller is basically a voltage and/or current regulator to keep batteries from overcharging and over discharging. This device regulates rates of flow of electricity from the generation source (panels) to the battery and the load. When the load is drawing power, the controller allows the charge to flow from the panels into the battery, the load, or both. When the controller senses that the battery is fully charged, it stops the flow of electricity from the generation source, or diverts it to an auxiliary or "shunt" load (most commonly an electric water heater). Also the controller senses when loads have taken too much energy from batteries (at set point of depth of discharge) and will stop the flow until

sufficient charge is restored to the batteries. This feature of the device helps to extend the battery life [22].

2.4.1.4 Solar batteries

A solar battery is a component that stores energy from a solar PV system. The system's panels absorb energy from the sun and convert it to electricity. It is an additional component that allows the user to store energy produced from the solar panels and use the energy at a later time when the panels are no longer producing energy [23]. It is also important to know that there are four (4) main different types of solar batteries which include Lead acid batteries, Lithium ion batteries, Nickel based batteries and Flow batteries. Figure 1 shows Katamanda battery bank configuration. The system consists of two hundred and seventy 2 V batteries with 30 batteries connected in series yielding nine (9) strings connected in parallel resulting into system voltage of 2V by 30 batteries equal to 60V.



Figure 1: Katamanda Solar Mini-Grid Battery bank

2.4.1.5 Racking

Racking refers to the mounting apparatus which fixes the solar array to the ground or rooftop. Typically constructed from steel or aluminum, these apparatuses are mechanically used to fix solar

panels in place with a high level of precision. Racking systems are designed to withstand extreme weather events such as hurricane or tornado level wind speeds and others. Another important feature of racking systems is to electrically bond and ground the solar array to prevent electrocution [22].

2.4.1.6 Other components

The remaining components of a typical solar PV system include combiners, disconnects, circuit breakers, meters and wiring. A solar combiner combines two or more electrical cables into one larger one. Combiners typically include fuses for protection and are used on all medium to large utility-scale solar arrays. Disconnects are electrical gates or switches which allow for manual disconnection of an electrical wire. Circuit breakers protect electrical systems from over current or surges. They are designed to trigger automatically when the current reaches a predetermined amount. An Electric meter measures the amount of energy that passes through it and is commonly used by electric utility companies to bill consumers [18].

2.4.2 PV system operation

The light from the Sun, made up of packets of energy called photons, falls onto a solar panel and creates an electric current through a process called the photovoltaic effect. Each panel produces a relatively small amount of energy, but can be linked together with other panels to produce higher amounts of energy as a solar array. The electricity produced from a solar panel is in the form of direct current (DC). Although many electronic devices use DC electricity, they are designed to operate using the electrical utility grid which provides (and requires) alternating current (AC). Therefore, in order for the solar electricity to be useful it must first be converted from DC to AC using an inverter. This AC electricity from the inverter can then be used to power AC electrical appliances. [18].

2.5 Types of PV Grids

Some of the PV grid types include off grid, mini-grid, grid connected (utility scale), and hybrid systems.

2.5.1 Off-grid solar PV system

An off-grid solar system is a standalone system and is designed for the power needs of mid-to-large size individual homes [24]. Since these systems have no connection with the utility grid, they must provide all the electricity necessary for a home. The systems operate from the stored energy in a battery bank charged by solar panels [25].

2.5.2 Solar mini-grid PV system

A solar mini-grid is a small scale electricity network fed by solar energy [3]. The generated electricity is supplied directly or indirectly via batteries to clients who are connected to this mini-grid electricity network [26][27]. A mini grid is also defined as a set of electricity generators and possibly energy storage systems interconnected to a distribution network that supplies electricity to a localized group of customers. They involve small-scale electricity generation (10 kW to 10 MW) which serves a limited number of consumers via a distribution grid that can operate in isolation from national electricity transmission networks [28] [29]. Figure 2 shows Chitandika solar mini-grid.



Figure 2: Chitandika solar mini-grid system

2.5.3 Utility scale or grid-connected solar PV system

A utility-scale solar facility is one which generates solar power and feeds it into the grid, supplying a utility with energy. Therefore, it is a power generation system that is connected to the grid [30]. This power does not need a battery bank [31]. Hence power is directly injected into the national utility grid upon generation for further distribution and supply to consumers [32]. The power generated from on-grid PV systems is used as supplement to the nation's power supply. Virtually every utility-scale solar facility has a power purchase Agreement (PPA) with a utility, guaranteeing a market for its energy for a fixed term of time.

2.5.4 Hybrid systems

A hybrid energy system is one that usually consists of two or more renewable energy sources used together to provide increased system efficiency as well as a greater balance in energy supply. To provide 100% power supply to a load, two or more renewable energy systems can be combined to fulfill the power requirements of the load. For example, 30% power can be derived from biomass system, 20% from wind systems and 50% from solar energy.

CHAPTER 3

3.0 RESEARCH METHODOLOGY AND MATERIALS

3.1 Overview

This chapter explains the research procedures which were applied in carrying out the study. It describes how the intended research objectives were achieved. The chapter covers; Research design, study area, study population, sample size, data collection methods (primary and secondary data), data analysis, dimension of sustainability (technical, economic, environmental, and social) and ethical issues.

3.1.1 Research design

A mixed methods design also known as *embedded design* was used in this work. This is a procedure for collecting, analyzing, and mixing both qualitative and quantitative research methods in a single study to deeply understand a research problem. This study employed a qualitative approach in collecting information about the people's opinions and perceptions towards the installation of solar mini grids. On the other hand, a quantitative approach was employed on the technical part of the research to help in quantifying the problem by way of generating numerical data that was transformed into usable statistics. Qualitative research is descriptive and thus focuses on meaning and understanding [33].

3.1.2 Study area

As stated in chapter one, the study was conducted at Chitandika solar mini-grid (Eastern Province), Katamanda solar mini-grid (Eastern Province), Magodi solar mini-grid (Eastern Province), Sinda solar mini-grid (Eastern Province) and Chibwika solar mini-grid (North Western Province). It was conducted within a natural setting of the communities such that participants were comfortable and provided the necessary information for the study. Questionnaires were administered at the comfort of their places of residence. Technical data was collected at the mini-grids location area.

3.1.3 Study population

The study population was drawn from all selected communities as stated above (study area). The study targeted participants who were aged 20 years and above as it was believed that this age range was able to have sufficient data at their disposal on the benefits and challenges of solar mini-grid installation in the selected areas. Due to limited resources, data was collected from the community houses, Rural Health Centres, rural school and churches as it was believed that a sample of such a number would give adequate information to attain the study objectives.

3.1.4 Sample size

The study selected a sample size of fifty (50) Chitandika households, ninety-two (92) Katamanda households, fifty-one (51) Sinda households, fifty-eight (58) Magodi households, and sixty-six (66) Chibwika households. These households were purposely selected as it was assumed that they could provide the needed information on the research topic under study. In addition, schools and rural health centers which were connected to the mini grid were sampled as well.

3.1.5 Data collection method

In the process of data collection, different instruments were employed. The internet was taken as the first step to obtain information. The researcher undertook visits to SMGs sites and Solar mini-grid developers and contacted other government agencies in energy such as Ministry of Energy (MoE), Energy Regulation Board (ERB), Rural Electrification Authority (REA). Information such as project location, developer, size of the plant, various technical details, land requirement, source and amount of financing, tariff structure, status, challenges, lessons learnt, completion period, environmental impact assessment, operational parameters and challenges, were collected and learnt during such visits. However, not all the required information for the study could be obtained since most mini-grid owners did not freely provide the data as they thought the project was not just for academic purposes. Research instruments used in data collection were questionnaires and semi-structured interview guides. A semi-structured administered questionnaire was adopted because it makes it easy for the respondents to answer. Additionally, the enumerator would be available to clarify if the question is not clear and would help the researcher to analyze data in a systematic way. On the other hand, Key Informant Interviews (KIIs) were used to collect qualitative data. Relevant questionnaires were used

as a tool of collecting data such as type of energy they used for television sets, radio cassettes, hammer mills and others before the establishment of the solar energy initiatives. Primary data consists of transcribed interviews and notes from non-recorded interviews, as well as field notes documenting observations, reflections and thoughts. These interviews lasted between thirty minutes to two hours and subsequently transcribed. The interviews were captured through notes taken at the time of the interview and elaborated further through extended field notes at the end of each day.

3.1.6 Primary Data

Primary data was gathered during a two-month period from September to October 2020. Interviewees from firms included senior staff with key roles in the firm's daily operations and staff with on-site operational responsibilities. Experts directly involved in decision-making processes were also targeted, as well as personnel who had specific and practical knowledge in the energy sector. Interviews were guided by a protocol that was continuously updated after each interview. The protocol or interview guide was developed prior to the fieldwork by operationalizing the central analytical concepts. This work included formulating relevant questions to ensure that the analytical concepts were covered and hence to improve validity in data collection.

3.1.7 Secondary data

Various documents on rural solar electrification and other information about the five (5) SMGs were used to perfect the primary data collection. Some of the secondary data was obtained from mini-grid owners and managers.

3.2 Data Analysis

Data analysis is the process of breaking a complex topic or substance into smaller parts to gain a better understanding [34]. Being a process, data analysis follows a series of stages, beginning from the time when the data is considered to be raw, up to the time when that data becomes information. It is the data that a researcher interprets in order to come up with conclusions and recommendations of the research [35]. Data analysis is therefore a significant aspect of every academic research. In analyzing the data, notes were taken and therefore most of the data was analyzed qualitatively. However, to analyze the technical designs and configuration of the solar mini-grids and to assess the

daily energy load requirement of community and others, the quantitative approach was employed. Excel and Statistical Package for the Social Sciences (SPSS) were used to analyze data collected.

3.3 Dimension of sustainability of studied solar mini-grids

In this section an overview of the four dimensions of sustainability considered in the study which include, technical, economic, environmental, and social dimensions of sustainability are presented.

3.3.1 Technical sustainability

The section assesses the functionality and reliability of the solar mini-grid systems over the expected life span. In other words, the ability of the solar mini-grid systems under examination to supply the expected amount of energy without technical maintenance beyond the required or expected life cycles [36]. Technical configurations of the PV system, i.e. batteries, solar inverter, charge controller, solar modules as in level of their quality to stand for a specific period of their lifespan are also discussed in this section.

3.3.2. Economic sustainability

Economic sustainability concerns the evaluation of the overall economic and financial well-being of the projects understudied. In other words, the economic sustainability covers the management of costs and revenues of the systems [37]. As a qualitative study without access to the financial accounts of the projects, a number of indicators were employed to assess the sustainability of the economics of each system to meet its operation and maintenance costs throughout its life span. Major issues of concern here included funding, tariff structure, revenue-generation, costs, business model, willingness, and ability to pay.

3.3.3 Environmental sustainability

An assessment of the Environmental sustainability of energy projects is crucial due to the overlap between energy and the environment. Environmental sustainability examines the impact of the projects understudy on the environment [38]. Issues of concern here include sources of emissions from electricity generation and use, reduction in less clean energy alternatives, reduction in indoor pollution, deforestation, among others. It also deals with the impact of a project on the environment

at the local, regional, and global levels. This covers issues like carbon savings (thus, reduction in environmental pollution) from the use of wood fuel, kerosene, and candles, among other fuels. It also covers the impact of the project on deforestation, flooding, and the workload for women and children in sourcing for wood fuel [39].

3.3.4 Social sustainability

Social sustainability is a critical part of any business because it affects the quality of a business' relationships with stakeholders. It is a proactive way of managing and identifying business impacts on employees, workers in the value chain, customers, and local communities [40]. This dimension of sustainability covers strategies for social inclusiveness employed towards the sustainability of the projects and concerns the social activities carried out at the inception of the project prior to deployment. Sustainability in this case includes needs identification, scope of the assessment of energy needs, level of community consultation, level of satisfaction to the provision of electricity, socialization activities, community engagement, ownership, and security of the system.

3.4 Ethical Consideration

Ethics is a matter of principled sensitivity to the rights of others. Being ethical limits the choices we can make in the pursuit of truth. Ethics says that while truth is good, human dignity is better, even if in the extreme case, the respect of human dignity leaves one ignorant of human nature [41]. Researchers are always reminded to remember that while they are doing their research, they are in actual fact entering the private spaces of their participants. This, therefore raises several ethical issues that should be addressed during, and after the research has been conducted. Furthermore, the researcher has an obligation to respect the rights, needs, values and desires of the informants [33]. In this regard, respondents were assured that the data collected from them would be used for academic purposes only. It was clearly stipulated that all the information collected from the respondents would not be exposed, and thus confidentiality of their identity was guaranteed. Finally, there was informed consent for the respondents to sign and show that they could participate willingly in the research and exercise their right to be part of the research.

CHAPTER 4

4.0 RESULTS AND DATA ANALYSIS

Findings from five (5) SMGs are reported here-in in terms of aspects on economic (business, tariff analysis), technical configurations (system sizing/energy demand), social, and environmental sustainability.

4.1 Chibwika solar mini-grid

Figure 3 shows the 32.4 kWp Chibwika SMG. The plant is located in Mwinilunga district of North Western Province at Chief Chibwika. It was commissioned in December 2019 through a grant from a Chinese company HUAWEI. The plant is operated by the community under the Chief. It supplies electricity to 108 households, one school, one Rural Health Centre, and has no commercial users.



Figure 3: Chibwika solar mini-grid

4.1.1 Economic sustainability

As stated in the methodology, economic sustainability concerns the evaluation of the overall economic and financial well-being of the projects under study. In other words, the economic sustainability depends on the costs and revenues of the systems. Major issues of concern here include funding, tariff structure (fixed or prepaid), sources of income, average yearly income, income spread,

income expenditure, capital and operational expenses, existence of bank accounts, willingness to pay, ability to pay among other economic issues.

4.1.1.1 Funding and cost of the plant

This solar mini grid is community owned and was donated by Chinese tech giant Huawei. The project has cushioned electricity demand of local residents. It has effectively improved their living standards, and promoted the development of culture, education and health services. The financing of the project was not availed to the researcher, but appears to be funded through a grant.

4.1.1.2 Tariff structure and business model

The system tariff structure is fixed and the customers are charged ZMW 50 (USD 3.13) monthly regardless of the appliances owned and how long they use electricity every day. This makes customers that use only bulbs for lighting complain as they feel their consumption is less compared to others who own fridges, TVs and other electrical appliances. However, the majority of customers are happy as they believe the price is low compared to the energy consumption.

The business model of the system is not clearly outlined. The system is run by the community and the consumers of electricity believe the mini grid was donated for free. So they are highly resistant to an increase in the tariff plan and mostly are not willing to go into commercial activities such as hammer mills, welding machines and grinders. The plant also supplies electricity to a nearby school and a rural health center.

4.1.1.3 Socio economic profile (occupation, average yearly income, income spread, willingness to pay for electricity, and typical expenditure)

The major source of income in chief Chibwika area is farming and bee keeping for honey with only a few civil servants on government salary. 33.4% of respondents have an average annual income of above ZMW 9,000, 22.7% earned between ZMW 5,001 and ZMW 7,000, 16.7% earned between ZMW 7,001 and ZMW 9,000 followed by 13.6% who earned between ZMW 3,001 and ZMW 5,000. 9.1% earned between ZMW 1,001 and ZMW 3,000 whereas the minority of the respondents 4.5%

had an average yearly income of below ZMW 1,000. The results are summarized in Table 1 and Figure 4.

Table 1: Occupation of Chibwika residents

| Occupation | Respondents | Percentage |
|---------------------------|-------------|------------|
| Farmers | 50 | 75.8 |
| Fishermen | 1 | 1.5 |
| Businessmen/Businesswomen | 3 | 4.5 |
| Civil Servants | 12 | 18.2 |
| Total | 66 | 100 |

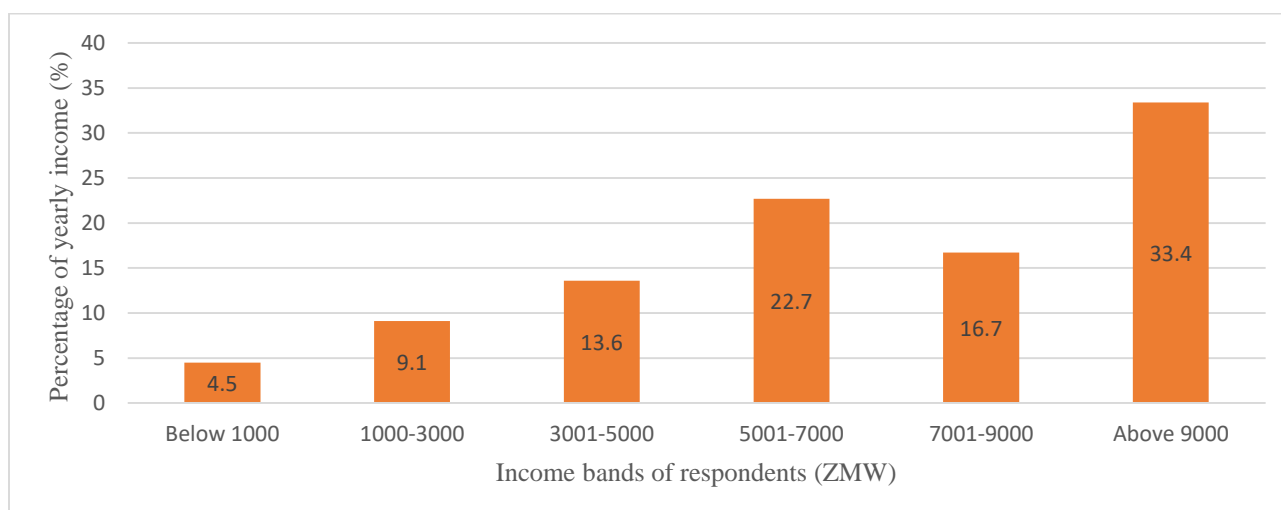


Figure 4: Average yearly income for chibwika SMG

The study also investigated how the earned income of Chibwika residents is spread daily, weekly, monthly and annually. The results in Figure 5 indicates the majority of the respondents 60.6% have their incomes spread annually. Peak income months are between April and September while the low income months are between October and November. This is because their income source is highly dependent on maize farming which done once in a year.

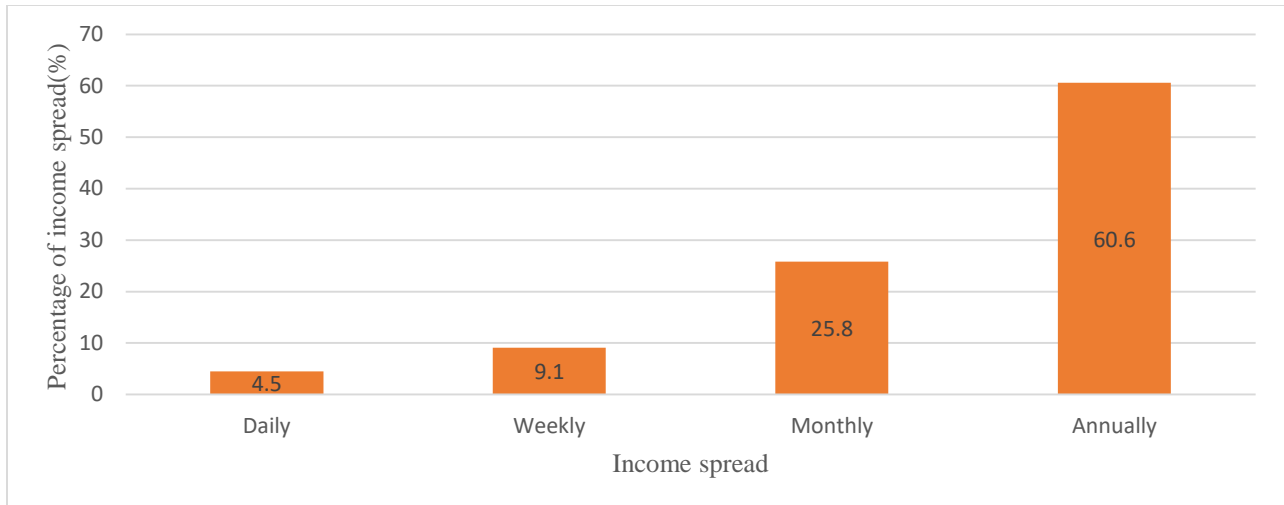


Figure 5: Income spread for Chibwika residents

Table 2 indicates that the majority of the respondents spend their income on school fees which accounted for 29.0%, whereas the minority of the respondents 19.2% spend their incomes on groceries. Similarly, 27.5% spend on food and 24.4% spend on energy.

Table 2: Family's typical expenditure for Chibwika residents

| Family expenditure | Responses | Percentage |
|--------------------|-----------|------------|
| Food | 53 | 27.5 |
| Groceries | 37 | 19.2 |
| School fees | 56 | 29.0 |
| Energy | 47 | 24.3 |
| Total | 193 | 100.0 |

As shown in Figure, majority of Chibwika community willing to pay for electricity between ZMW 50 and ZMW 100 per month is 63.5% the reason being the solar mini-grid was given as a gift and hence there was no need to pay.

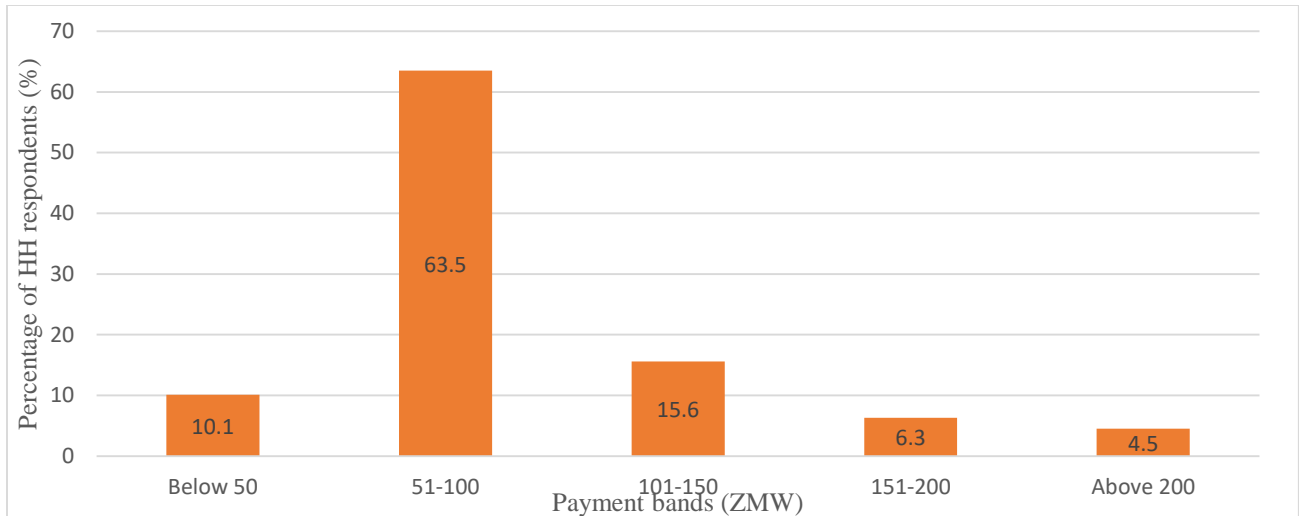


Figure 6: willingness to pay for electricity per month of Chibwika residents

4.1.1.4 Sustainability assessment

In order to analyze sustainability assessment, the money generated per month and per year was calculated and compared with the total operational costs (maintenance costs and salaries for the workers). This part calculates the sustainable tariff estimation.

4.1.1.4.1 Monthly and yearly revenues

Chibwika solar mini-grid supplies power to a total number of 108 households, a school and a clinic with a fixed tariff payment of ZMW 50 per household in a month. It is clear that the plant generates a maximum of ZMW 5,400 per month from the households plus an addition of ZMW 200 from a school and a clinic. Assuming the plant works perfectly and no one defaults in payments, the plant is capable of making $ZMW\ 5,600 \times 12\ months = ZMW\ 67,200$ equal to USD 4,200 using the current ZMW 16 to 1 USD. The CAPEX will not be included in the calculations since the mini-grid was given as a gift to the community.

4.1.1.4.2 Operational costs and salaries for workers

For the plant to run well, it requires maintenance (day-to-day up-keep) addressing any technical issues and replacement of parts such as batteries, inverters and charge controllers as they worn out. To calculate the battery, inverter and charge controllers replacement costs, the general costs of individual

solar components were used to come up with the amount of money required to replace these components after their life span. Table 3 shows different prices of solar components sourced from Muhanya Solar Limited and other solar companies based in Zambia like DS solar, Solar Macs energy as well as the internet using Alibaba.com.

Table 3: Price of Solar components and their specification

| Solar components | Specification | Price (USD) | Price (ZMW) |
|-------------------------|---------------------------|--------------------|--------------------|
| Batteries | 120 Ah/3.2 V LiFePo4 | 281 | 4,496 |
| | 150 Ah/2 V LiFePo4 | 342 | 5,472 |
| | 550 Ah/6 V flooded | 406 | 6,496 |
| | 1175 Ah/2 V flooded | 918 | 14,688 |
| | 600 Ah/2 V Lead acid | 237 | 3,792 |
| | 1000 Ah/2 V lead acid | 400 | 6400 |
| Charge controllers | 50 A PWM | 281 | 4,496 |
| | 60 A MPPT | 1,025 | 16,400 |
| | 100 A PWM | 700 | 11,200 |
| Inverter | 5 kW Hybrid inverter/48 V | 1,148 | 18,368 |
| | 6 kVA | 1,000 | 16,000 |
| | 8 kVA | 1,093 | 17,488 |
| | 12.5 kW | 1,750 | 28,000 |
| | 50 kVA | 2,312 | 36,992 |

The above prices in Table 3 were taken as the standard prices to calculate estimated annual maintenance costs. A summary of the estimate of annualized maintenance and overhead cost is provided in Tables 4 and 5. Take note that the replacement of solar batteries is done approximately every after five years with inverters and charge controllers replaced after ten years, taken as the minimum life expectancy of the components.

Table 4: Estimated total replacement and annual maintenance cost

| Number of components | Total replacement cost (USD) | Price (ZMW) | Lifetime (years) | Annualized cost (USD) | Annualized cost (ZMW) |
|--------------------------|------------------------------|-------------|------------------|-----------------------|-----------------------|
| 256, 3.2V Batteries | 72,000 | 1,152,000 | 5 | 14,400 | 230,400 |
| 1, 50kW inverter | 2,312 | 37,000 | 10 | 231 | 3,700 |
| 1, 50A Charge controller | 281 | 4,500 | 10 | 28 | 450 |
| Miscellaneous | | | | 125 | 2,000 |
| Sub-total | | | | 14,784 | 236,550 |

Equation (1) is used to calculate annualized replacement cost.

$$\text{Annualized cost} = \frac{\text{total component cost}}{\text{life span of component}} \dots\dots\dots (1)$$

where

$$\text{Total component cost} = \text{number of components} \times \text{price of each component} \dots\dots\dots (2)$$

Table 5: Estimated overhead costs for the five (5) SMGs

| Staffs | Monthly Salary (USD) | Annual salary (USD) |
|------------------------|----------------------|---------------------|
| Manager/Accountant (1) | 500 | 6,000 |
| Technician (1) | 400 | 4,200 |
| Security Guard (2) | 200 | 4,800 |
| Other expenses | 100 | 1,200 |
| Total | | 16,200 |

At least one manager/accountant, a technician and two security guards are required to maintain the operation of a solar mini-grid.

The total annual cost is calculated in Tables 4 and 5 as USD 14,784 + USD 16,200 = USD 30,984. Comparing this amount of money to USD 4,200 plant’s yearly revenue clearly indicates that the plant is currently operating at a loss making it highly financially unsustainable.

4.1.1.4.3 Sustainable tariff estimation

A sustainable plant requires revenue generated from the sale of solar energy being able to meet all the operational costs and overhead costs. Therefore, estimated sustainable tariff plan is calculated using equation (3) and (4) as completed in Table 6.

$$\text{Annual energy generation} = \text{total plant capacity} \times \text{solar irradiation} \times 365 \text{ days} \dots\dots (3)$$

$$\text{Sustainable tariff} = \frac{\text{total annual cost}}{\text{annual energy sold}} \dots\dots\dots (4)$$

Table 6: Annual energy generated and tariff estimation for Chibwika SMG

| Item | Size/Value |
|--|------------------------------|
| Total System capacity (kWp). | 32.4 |
| Average solar irradiation in the area (kWh/m ² /day). | 5.742 |
| Energy generated daily (kWh). | 32.4 x 5.742 = 186 |
| Annual energy generation (kWh). | 186 x 365 = 67,890 |
| After 20% energy losses (kWh). | 67,890 x 0.8 = 54,312 |
| Annual energy sold 80% (kWh). | 54,312 |
| Sustainable Tariff (per kWh). | USD 30,984/54,312 = USD 0.57 |

Table 6 shows that the operation and overhead sustainable tariff is USD 0.57/kWh which is equivalent to ZMW 9.12 at the current rate of 1 USD equal to ZMW 16. The rate greater than the current ZESCO 2021 residential tariff of about ZMW 1.15 per unit for consumption ranging between 101 to 300 units. The sustainable tariff for the solar mini-grid is too high as compared to ZESCO tariffs because utility tariffs generally have significant subsidies and are not cost reflective. The other reason is that solar mini-grids operate at a smaller level, so their overhead costs are relatively high and they also need replacement of batteries, charge controllers and inverters after a certain period of time.

Calculations of the average amount of money required per household to run the plant sustainably with no subsidies are as follows. The plant's yearly revenue is estimated to be USD 4,200 which is just 14% of the required OPEX and overhead costs. Assuming the plant works at full capacity and the number of houses connected increase to 200, the average cost per household would be USD 30,984/200 households = USD 155 per household per annum or USD 13 (ZMW 207) per household per month. Even though highest percentage of Chibwika residents have an average yearly income above ZMW 9,000, most of their expenditures are on food and school fees with less money spared

for electricity. Their willingness to pay for electricity per month was only around ZMW 100 which is not good enough to attain the plants sustainable tariff. It was found that even at a cost of ZMW 50 per month, some households still default. This clearly indicates that a collection of ZMW 207 per month from the households would be difficult and this makes Chibwika solar mini-grid unsustainable. It is important to note that these above sustainable tariff calculations do not include the capital expenditure of the mini-grid.

4.1.2 Technical sustainability (configuration and specifications)

This section focuses on the technical configurations of the solar mini-grids. It gives details such as the total capacity of the mini-grid, the number of solar PV modules, batteries, inverters and charge controllers even though in some cases full information of technical details such as battery connections and capacity was difficult to find because some batteries, charge controllers, and inverters were not labeled and some were imbedded in one component. The configuration and specifications of the components is mostly summarized in tabular form. This section also looks at energy generated by the solar mini-grids in comparison to the energy demand of the community.

4.1.2.1 Solar PV modules

The solar PV module specification and configuration is given in Table 7 and Table 8.

Table 7:Chibwika Solar PV module specification

| | |
|--------------------------------------|---------------|
| Manufacturer | SUNTECH |
| Model | STP270-20/Wfw |
| Number of modules | 120 x270W |
| Voltage at P_{max} (V) | 31.1 |
| Current at P_{max} (A) | 8.69 |
| Module efficiency (%) | 17 |
| Power tolerance (%) | 0/+5W |
| Temperature coefficient of V_m (%) | -0.304/degree |

Table 8: Chibwika solar PV module configuration

| | |
|------------------------------------|-------------------------|
| Solar PV module orientation | North |
| Solar PV module inclination | 20 degrees |
| Total number of solar PV modules | 120 |
| Number of PV modules in a string | 20 in series |
| Number of strings in parallel | 6 |
| String voltage (V) | $31.1 \times 20 = 622$ |
| String current (A) | 8.69 |
| Maximum total charging current (A) | $6 \times 8.69 = 52.14$ |

4.1.2.2 Batteries

With reference to Table 9, the mini-grid uses Lithium Ion Phosphate batteries and is based on a modular concept. A single battery module is composed of 8 submodules which are connected in series with each submodule consisting of 16 cells connected in series each having a nominal voltage of 3.2 V. Each battery module has a voltage of 409.6 V and 120 Ah battery capacity. There are a total of two modules connected in parallel to yield a battery bank capacity of 240 Ah with usable battery capacity of 120 Ah at 50% DoD. The batteries are controlled and monitored by a master battery unit which is in turn linked to all the cells in both the battery modules and has the ability to report each individual cell, including voltage and temperature. The master battery is responsible for switching on and shutting down the batteries when need arises.

Table 9: Battery specification & configuration

| | |
|--|--------------------------|
| Technology | Lithium Ion Phosphate |
| Manufacturer | Not given |
| Model | Not given |
| Total number of batteries | 256 |
| Number of batteries in a string | 128 |
| Cell voltage (V) | 3.2 |
| String voltage (V) | $128 \times 3.2 = 409.6$ |
| Battery capacity (Ah) | 120 |
| Total battery capacity (Ah) | $2 \times 120 = 240$ |
| Usable battery capacity (Ah) @ 50% DoD | 120 |

4.1.2.3 Inverters, charge controllers and backup diesel generator

The plant uses one three phase inverter with rated power of 50 kW with an output voltage of 480 V and output current of 104 A. The inverter has the ability to receive power on the AC Bus from an alternative source such as a generator in line with the design of the system. On the other hand, one charge controller rated 50 A is used to control charging and discharging of the batteries. The system controller is connected to the power conditioning unit (generator and battery bank) making it able to report on the status of each of the facilities including the energy generated from the photo-voltaic modules. The power plant is also equipped with a 44 kVA three phase backup Cummins diesel generator that provides auxiliary power in the case of batteries going below 20% state of charge. A summary of the configurations is shown in Table 10 and Table 11.

Table 10: Inverter Specification & Configuration of Chibwika SMG

| | |
|---------------------------|-----------|
| Manufacturer | Not given |
| Model | Not given |
| Technology | Not given |
| Phase type | 3 |
| Total number of inverters | 1 |
| Rated power (kW) | 50 |
| Total rated power (kW) | 50 |
| Protection type | Not given |

Table 11: Charge controller type and configuration of Chibwika SMG

| | |
|------------------------------------|-----------|
| Manufacturer | Not given |
| Model | Not given |
| Technology | PWM |
| Total number of charge Controllers | 1 |
| Charge controller rating (A) | 50 |
| Total Charge controller rating (A) | 50 |

4.1.3 Daily energy load in comparison with system size

To compare system size with load requirement, data on various electrical appliances used by households, school, and clinic were collected. Their average power consumption and daily operational hours were used to calculate the energy consumption of the communities. The calculations were done as shown in Table 12 and a comparison was made to check if the systems were oversized, undersized or well sized.

Table 12: Energy consumption of Chibwika residents

| Devices | Quantity | Wattage (W) | Total wattage (W) | Operation hours | Energy(Wh) = total wattage x time |
|--------------------|----------|-------------|-------------------|-----------------|-----------------------------------|
| Televisions | 42 | 100 | 4,200 | 10 | 42,000 |
| Satellite decoders | 30 | 21 | 630 | 10 | 6,300 |
| Fridges | 12 | 300 | 3,600 | 12 | 43,200 |
| Desktop Computers | 10 | 200 | 2,000 | 6 | 12,000 |
| Radios | 34 | 30 | 1,020 | 10 | 10,200 |
| Phone chargers | 40 | 6 | 240 | 6 | 1,440 |
| Bulbs | 434 | 15 | 6,510 | 10 | 65,100 |
| Total | | | | | 180,240=180.24 kWh |

Chibwika solar mini-grid daily energy consumption is almost equal to the plant's energy production of about $32.4 \times 5.742 = 186$ kWh (Table 6). After 20% energy losses, the system energy available for sale reduces to 149 kWh resulting in daily energy deficit of 31 kWh under sizing the plant by 5.40 kW. This means that there should be no additional load connections to the plant. Equation 5 is used to calculate the plant's total energy generation.

$$\text{Plant total energy generation} = \text{peak power} \times \text{area daily solar irradiance} \dots\dots\dots (5)$$

4.1.4 Challenges

Some of the challenges of the mini-grid include; (a) lack of professionalism in the running of the plant as well as little technical capacity among the community to run this system efficiently. Furthermore, the tariff is too low and fixed regardless of uses hence being deemed unfair; (b) system overloads at times due to the system circuit breaker rated at 16 A which is capable of operating a pressing iron and other elements and (c) the willingness and ability to pay does not tally.

4.1.5 Remedies

To remedy the identified challenges, the following can be suggested; (a) the operation of the plant should be given to a private company with clear terms of reference so that it runs like a business; (b) introduce prepaid metres or replace the circuit breaker and put one with a maximum current of 5 A; and (c) the income levels, ability and willingness of the residents to pay must go up through sufficient marketing to influence the community regarding the use of solar as being, healthy, clean and safe. In

the meantime, the government via necessary energy agencies like REA and others should support the project until the socio-economy of the area is improved through sensitization of uses of solar energy in productive uses.

4.2 Chitandika solar mini-grid

Chitandika SMG has 28.35 kWp total capacity. It is located in Chitandika village in Chipangali district of Eastern Province. It was commissioned in February 2019, and is operated by Engie Power Corner a private company. The SMG supplies electricity to 156 households, two (2) nearby schools, one (1) rural health centre, commercial users include two (2) hammer mills rated at 11 kW each, two (2) dehala machines rated at 7.5 kW each, one (1) 4.4 kW welding machine, one (1) 4 kW grinder, two (2) business hair salon and 29 pressure cookers. Figure 7 shows Chitandika SMG.



Figure 7 : Chitandika solar mini-grid

4.2.1 Economic sustainability

4.2.1.1 Funding and cost of the plant

This solar mini-grid is privately owned and was funded by ENGIE POWER CORNER at a cost of EUR 250,000(USD 312,500) comprising mainly equity 70% and a grant of 30% [42]. The business model has a focus on the productive use of electricity, enabling the unlocking of the economic potential of rural communities.

4.2.1.2 Tariff structure and business model

The business uses prepaid meters in the form of a spark meter for each household which is able to switch off power when the loaded units finish. The customers are given a mobile number which they use to purchase electricity and the electricity purchased is always in monetary form with 1 kwacha equivalent to a certain unit which was not availed. So when one purchases units of ZMW 100 and as he/she uses it, the money starts to reduce until ZMW 0.00 is reached and the spark meter automatically switches off the power.

The company has categorized the supply of energy as bundle types which includes bundles A, B, C, D and E. These bundle types are limited in the amount of energy they supply. Bundle A can only supply up to 40 W, Bundle B supplies up to 100 W, Bundle C supplies up to 3,000 W and finally the two bundles D and E are categorized as commercial bundles which are allowed to consume power even above 3,000 W with a limit of 5,000 W. In order to encourage customers to upgrade to higher level bundles like bundles D and E, the higher level bundles are made cheaper per unit of electricity than the lower level bundles, i.e. the most expensive bundle per unit of electricity is bundle A. When people in lower bundles try to use appliances with higher ratings than their allocated bundle type, the system trips and goes in check mode.

4.2.1.3 Socio economic profile (occupation, average yearly income, income spread and typical expenditure)

The major source of income for the community is farming and some businesses. Very few individuals were found to be working as civil servants. The results are shown in Table 13.

Table 13: Distribution of respondents by occupation

| Occupation | Respondent | Percentage |
|---------------------------|-------------------|-------------------|
| Farmers | 33 | 66 |
| Fishermen | 0 | 0 |
| Businessmen/businesswomen | 13 | 26 |
| Civil Servants | 4 | 8 |
| Total | 66 | 100 |

Average monthly income is a good indicator of the ability to pay for electricity from the solar mini grid. However, this study used the yearly average income estimate as it was found that the income

realized by the residents come at irregular intervals which made it difficult to estimate the monthly average income. Results in Figure 8 and Figure 9 indicate that 30% of the respondents have an average yearly income above ZMW 9,000, 22% between ZMW 1,000- ZMW 3,000, 20% between ZMW 3,001 and ZMW 5,000, 12% below ZMW 1,000, 10% between ZMW 5,001 and ZMW 7,000 with the minority 6% lying between ZMW 7,001 and ZMW 9,000. Most of the residents have their income spread annually which led to low energy sold in low income months.

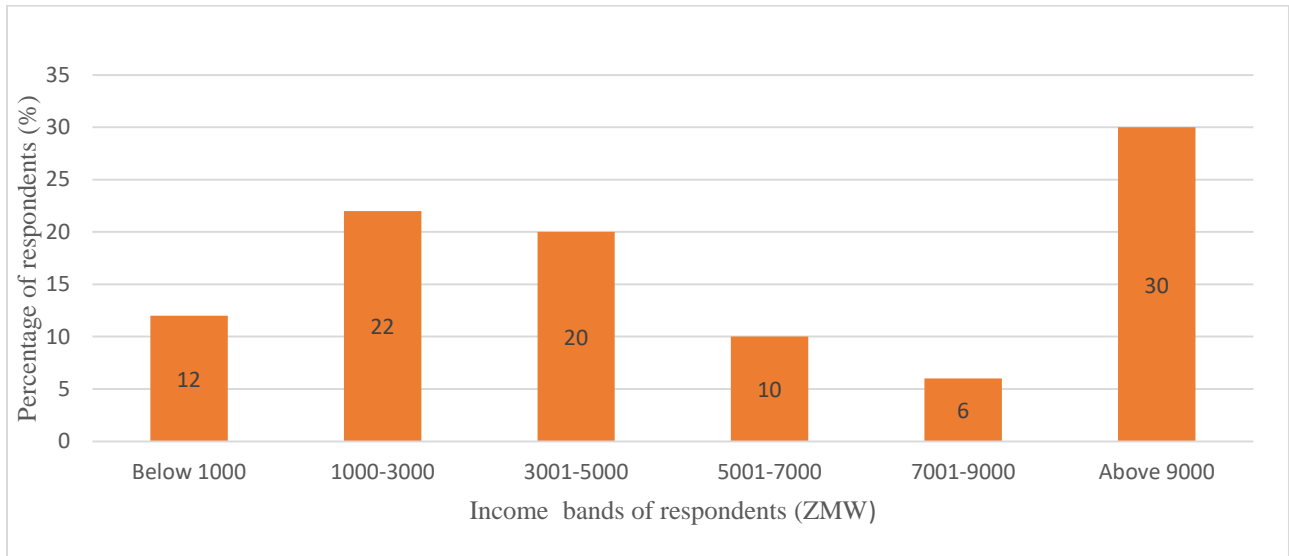


Figure 8: Average yearly income for Chitandika residents

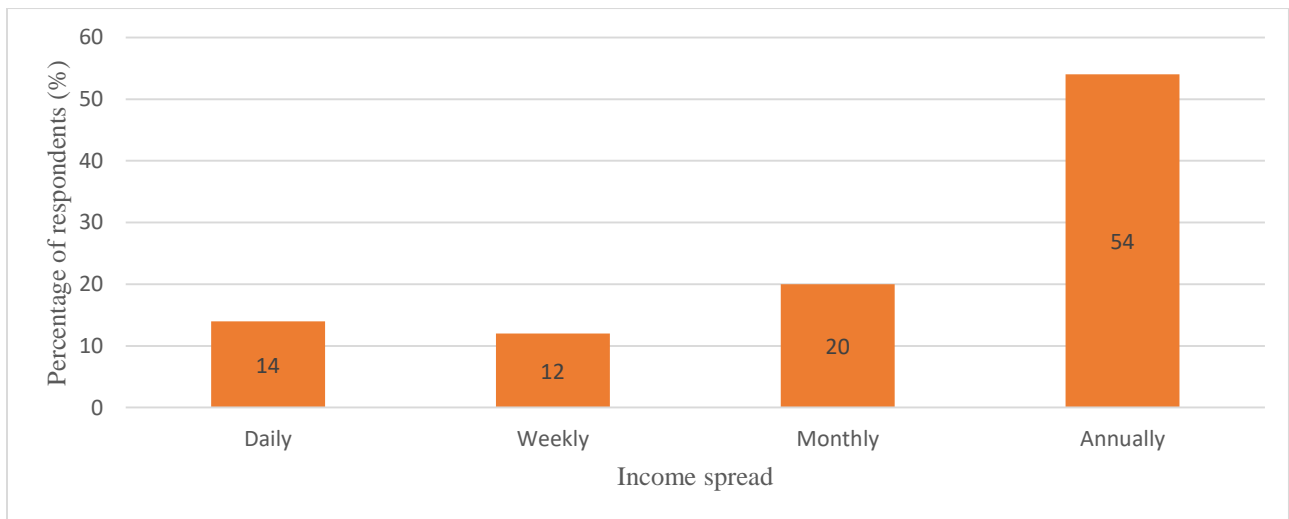


Figure 9 :Income spread for Chitandika residents

Table 14 shows typical expenditure of Chitandika residents. Majority of the residents spend their income on food (39.5%) and school fees (31%) with only 15.9% spend their money to buy electricity. It was found that people in bundles A and B spend about (ZMW 50 per month) for lighting and watching TV. Business people in bundles D and E spend an average of (ZMW 200 per month) for commercial purposes.

Table 14: Typical expenditure for family of Chitandika residents

| Family typical expenditure | Responses | Percentage |
|-----------------------------------|------------------|-------------------|
| Food | 45 | 39.8 |
| Groceries | 10 | 8.8 |
| School fees | 35 | 31.0 |
| Farm input | 5 | 4.4 |
| Energy | 18 | 15.9 |
| Total | 113 | 100.0 |

Data further indicated that majority of Chitandika residents were willing to pay for electricity an amount between ZMW 51 and ZMW 200 as shown in Figure 10.



Figure 10: Payment bands of Chitandika residents

4.2.1.4 Sustainability assessment

It is important to note that currently the workers at Chitandika SMG do not draw their salaries from the income generated by the SMG and hence there are no overhead costs. The tariff estimation therefore is based on annual maintenance costs and operation costs only.

4.2.1.4.1 Monthly and yearly revenues

From Tables 15 and 16 Chitandika SMG has a yearly revenue of ZMW 131,400 (USD 8,213) whereas the annual maintenance cost of ZMW 72,400 (USD 4,525).

Table 15: Monthly and yearly revenues of Chitandika solar mini-grid

| Number of connections | Monthly revenue | Yearly revenue |
|-----------------------|-------------------------|--------------------------|
| 156 Households | 156 x ZMW50 = ZMW 7,800 | ZMW 93,600 (USD 5,850) |
| 2 Hammer mills | 2 x ZMW 300 = ZMW 600 | ZMW 7,200 (USD 450) |
| 2 Dehala machines | 2 x ZMW 250 = ZMW 500 | ZMW 6,000 (USD 375) |
| 1 Welding machine | 1 x ZMW 150 = ZMW 150 | ZMW 1,800 (USD 112.5) |
| 1 Grinder | 1 x ZMW 150 = ZMW 150 | ZMW 1,800 (USD 112.5) |
| 2 Hair saloons | 2 x ZMW 150 = ZMW 300 | ZMW 3,600 (USD 225) |
| 29 Pressure cookers | 29 x ZMW 50 = ZMW 1,450 | ZMW 17,400 (USD 1,087.5) |
| Total revenue | ZMW 10,950 | ZMW 131,400 (USD 8,213) |

The money made from the operation of the plant is deposited in the company's bank account. Comparing the CAPEX with the total year revenue, it would take about 38 years for the plant to reach the breakeven point for CAPEX alone without OPEX and overhead costs. This is practically impossible because solar components need replacements and maintenance. The solar panel lifespan is about 25 to 30 years, with inverters, charge controllers and batteries at 10 years, 10 years and 5 years respectively. This is less than the breakeven point. However, operational sustainability can be looked at if we assume the plant was a donation like many of the community owned mini-grids.

Table 16: Estimated annual maintenance cost for Chitandika SMG

| Number of components | Current replacement price (USD) | Price (ZMW) | Lifetime (years) | Annualized cost (USD) | Annualized cost (ZMW) |
|---------------------------|---------------------------------|-------------|------------------|-----------------------|-----------------------|
| Batteries (48x2V) | 19,200 | 307,200 | 5 | 3,840 | 61,440 |
| Inverters (2x12.5kW) | 3,500 | 56,000 | 10 | 350 | 5,600 |
| 3x100A Charge controllers | 2,100 | 33,600 | 10 | 210 | 3,360 |
| Miscellaneous | | | | 125 | 2,000 |
| Sub-total | | | | 4,525 | 72,400 |

4.2.1.4.2: Sustainable tariff estimation

Table 17 clearly shows that the operation sustainable tariff is USD 0.095/kWh equivalent to ZMW 1.52/kWh at the current rate of 1 USD equal to ZMW 16. The rate which is closer to that of ZESCO 2021 residential tariff of about ZMW 1.15 per unit for consumption ranging between 101 to 300 units. This is possible only if the solar mini-grid is working at full capacity during its life-time operational.

Table 17: Annual energy generated and tariff estimation for Chitandika

| Item | Size/Value |
|--|---------------------------|
| Total system capacity (kWp). | 28.35 |
| Average solar irradiation in the area (kWh/m ² /day). | 5.775 |
| Energy generated daily (kWh). | 28.35 x 5.775 = 164 |
| Annual energy generation (kWh). | 163.721x 365 = 59,758 |
| After 20% energy losses (kWh). | 59,758.165 x 0.8 = 47,806 |
| Annual average energy sold 80% (kWh). | 47,806 |
| Sustainable tariff (USD/ kWh). | 4,525/47,806 = 0.095 |

Calculations on the average amount of money each household should pay to make the plant sustainable is done. From Table 15, the annual revenue of Chitandika SMG looks good for operational sustainability. Assuming the plant is working at full capacity and take the number of households connected increase to 200 and estimate commercial users such as hammer mills, grinder, pressure cookers, saloons, schools and a clinic equal to 80 household connections. A total number of 280 households could be connected to the plant. Therefore, the average cost per household to generate sufficient revenue to meet maintenance cost = USD 4,525/280 households = USD 16/household per annum (ZMW 256/household per annum) translating into ZMW 256/12 = ZMW 21 per month which is very low in comparison to a tariff structure that covers, OPEX, CAPEX, and overhead costs.

However, if the overhead costs are included, the tariff structure will go high and this gives a true reflection of sustainable tariff of [(USD 4,525 + USD 16,200)/47,806 kWh] = USD 0.43/kWh. This requires each household to pay about USD 74 (ZMW 1,184) per year translating into ZMW 99 per month. This lies well for Chitandika residents as their average yearly income lies between ZMW 3,000 and ZMW 9000 and the willingness to pay for electricity ranges between ZMW 50 to ZMW 200 per month. The fact that Chitandika residents are willing to pay an amount above ZMW 50 per household and the maintenance and overhead costs only requires them to pay at least ZMW 99 per month makes this plant partially financially sustainable.

4.2.2 Technical sustainability (configuration and specifications)

4.2.2.1. Solar PV modules

Table 18 and Table 19 show the specifications and configuration of the PV modules respectively.

Table 18: Chitandika Solar PV modules specification

| | |
|--------------------------------------|----------------|
| Manufacturer | Renesola |
| Model | JC 270M-24/Bbw |
| Number of modules | 105 |
| Voltage at P_{max} (V) | 31.0 |
| Current at P_{max} (A) | 9.16 |
| Module efficiency (%) | 15 |
| Power tolerance (%) | ± 3 |
| Temperature coefficient of V_m (%) | -0.37 |

Table 19: Chitandika Solar PV configuration

| | |
|------------------------------------|--|
| Solar PV module orientation | North, South and West |
| Solar PV module inclination | 30 degrees |
| Total number of solar PV modules | 105 |
| Number of PV modules in a string | 4 strings of 15 modules in series, 1 string x 22 and 1 string x 23 |
| Number of strings in parallel | 6 |
| String voltage (V) | 465, 682, and 713 |
| String current (A) | 9.16 |
| Maximum total charging current (A) | $6 \times 9.16 = 54.96$ |

4.2.2.2 Batteries

Table 20 shows battery specification and configuration.

Table 20: Battery Specification & configuration

| | |
|--|------------------------|
| Technology | Lead acid, open vented |
| Manufacturer | NARADA |
| Model | NARADA REX |
| Total number of batteries | 48 |
| Number of batteries in a string | 24 |
| Cell voltage (V) | 2 |
| String voltage (V) | 48 |
| Battery capacity (Ah) | 1000 x 2 = 2000 |
| Total battery capacity (Ah) | 2,000 |
| Usable battery capacity (Ah) @ 50% DoD | 1,000 |

4.2.2.3 Inverters and charge controllers

The inverters are protected from lightning via surge arrestors. On the other hand, three charge controllers are used to control charging and discharging of the batteries. The inverter and Charge controllers specifications are shown in Table 21 and Table 22 respectively.

Table 21: Inverter specification

| | |
|---------------------------|-----------------|
| Manufacturer | FRONIUS SYMO |
| Model | FRONIUS SYMO |
| Technology | PWM |
| Phase type | 3 |
| Total number of inverters | 2 |
| Rated power (kW) | 12.5 |
| Total rated power (kW) | 25 |
| Protection type | Surge arrestors |

Table 22: Charge controller type and specifications

| | |
|------------------------------------|----------------|
| Manufacturer | Victron Energy |
| Model | Victron Quatro |
| Technology | PWM |
| Total number of charge Controllers | 3 |
| Charge controller rating (A) | 100 |
| Total Charge controller rating (A) | 300 |

4.2.3 Daily energy load in comparison with system size

Looking at the total daily energy requirement for Chitandika solar mini-grid of 468 kWh in Table 23 and in comparison to system's energy available for sale of 131kWh gives energy deficit of 337 kWh under sizing the plant by $(337 \text{ kWh}/5.775 \text{ kWh/m}^2/\text{day}) = 58 \text{ kW}$.

Table 23: Energy consumption of Chitandika residents

| Devices | Quantity | Wattage (W) | Total Wattage(W) | Operation hours | Energy(Wh) = total Wattage x operation hours |
|--------------------|----------|-------------|------------------|-----------------|--|
| Hammer mills | 2 | 11,000 | 22,000 | 5 | 110,000 |
| Dehala | 2 | 7,500 | 15,000 | 5 | 75,000 |
| Welding Machines | 1 | 4,400 | 4,400 | 5 | 22,000 |
| Grinders | 1 | 4,000 | 4,000 | 5 | 20,000 |
| Hair Blowers | 4 | 2,000 | 8,000 | 5 | 40,000 |
| Hair driers | 4 | 1,500 | 6,000 | 5 | 30,000 |
| Hair Straighteners | 4 | 80 | 320 | 5 | 1,600 |
| Pressure cookers | 29 | 1,000 | 29,000 | 4 | 87,000 |
| Fridges | 22 | 100 | 2,200 | 12 | 26,400 |
| Desktop Computers | 15 | 160 | 2,400 | 6 | 14,400 |
| Televisions | 40 | 65 | 2,600 | 4 | 10,400 |
| Radios | 50 | 30 | 1,500 | 6 | 9,000 |
| Bulbs | 453 | 5 | 2,265 | 10 | 22,650 |
| Total | | | | | 468,450 = 468.45 kWh |

4.2.4 Challenges

Some of the challenges at this mini-grid include; (a) inability to pay for electricity due to seasonal income and (b) general feeling by the customers that tariffs are too high and believe that they are being exploited as money is not converted into units of electricity (kWh).

4.2.5 Remedies

As a redress to some of these challenges, solar mini-grid owners should (a) encourage customers to venture into different businesses such as, restaurants, irrigation, and others in order to generate income on a daily basis rather than depending on yearly income from maize farming; and (b) use of prepaid meters that will be able to convert money into units (kilowatt hours as energy consumed).

4.3 Katamanda solar mini-grid

The Katamanda SMG has a total power capacity of 51.8 kWp located in Chipangali district of Eastern Province in Tamanda village. It was commissioned in October 2017 as a gift to the community by the government through ETERN, a Chinese company. The SMG is operational, run by the community under the village headman. It supplies electricity to 273 households, 2 nearby schools, one rural health Centre, with no commercial users. Figure 11 is Katamanda solar mini-grid PV configuration.



Figure 11 Katamanda solar mini-grid PV configuration

4.3.1 Economic sustainability

4.3.1.1 Funding and cost of the plant

Katamanda solar mini grid was constructed and designed by ETERN company. It is community owned and was funded by the Chinese government as a gift to the Zambian government. The cost of the grid was not availed to the researcher.

4.3.1.2 Tariff structure and business model

The business uses fixed charge as mode of payment for electricity. The grid management imposed monthly charges towards connections to the grid, of the 273 households, one (1) Liquor shop, connected to the grid, an amount of ZMW 12 (USD 0.75) was paid by each household and a liquor shop every month. Two (2) Schools and 1 RHC connected to the grid paid ZMW 20 (USD 1.25) each month. Two (2) grocery shops connected to the grid also paid a fixed fee of ZMW 20 (USD 1.25) each per month. There was no clear information on how the monthly generated money was used as there was no bank deposit account for the mini-grid.

4.3.1.3 Socio economic profile (Occupation, average yearly income, income spread, willingness to pay for electricity, and typical expenditure)

The major source of income for the community based on the summarized data collected in Table 24 was found to be maize farming.

Table 24: Distribution of Respondents by Occupation for Katamanda

| Occupation | Respondents | Percentage |
|---------------------------|-------------|------------|
| Farmers | 85 | 92.4 |
| Fishermen | 0 | 0.0 |
| Businessmen/Businesswomen | 4 | 4.3 |
| Civil Servants | 3 | 3.3 |
| Total | 92 | 100 |

The results further indicated that the majority of Katamanda residents had an average yearly income ranging between ZMW 1,001 - ZMW 3,000. The results are shown in Figure 12 and Figure 13.

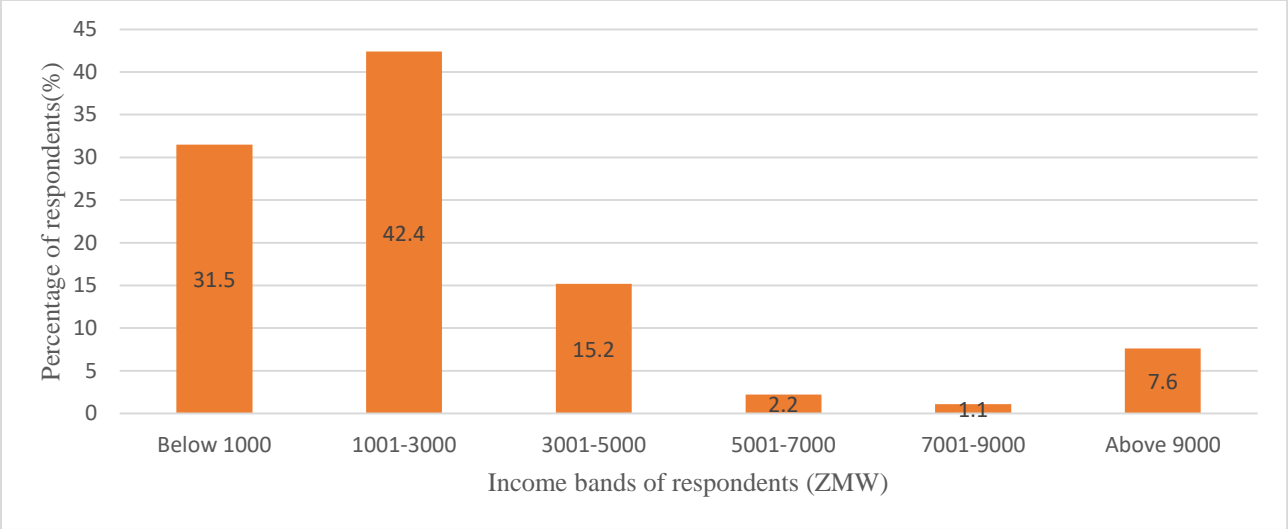


Figure 12: Average yearly income for Katamanda residents

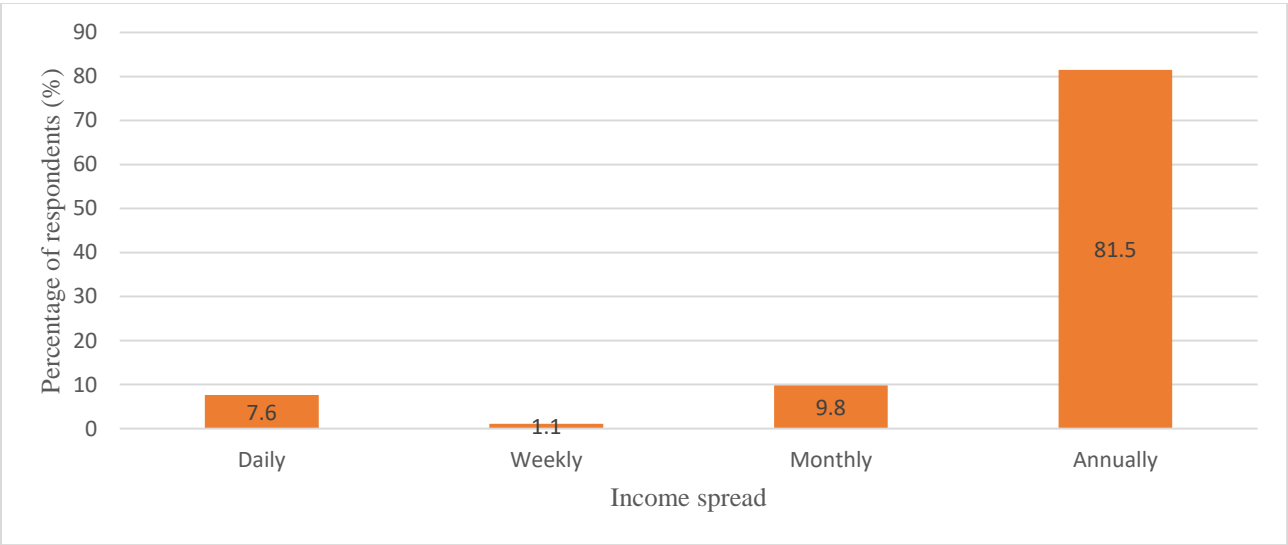


Figure 13: Income spread for Katamanda residents

In order to find out how people were comfortable to pay for electricity, the researcher asked the respondents how much they were willing to pay for electricity on a monthly basis if the mini-grid were to be extended. Data shows that the majority of the respondents (88%) were willing to pay below ZMW 50. Figure 14 summarizes the results on willingness to pay.

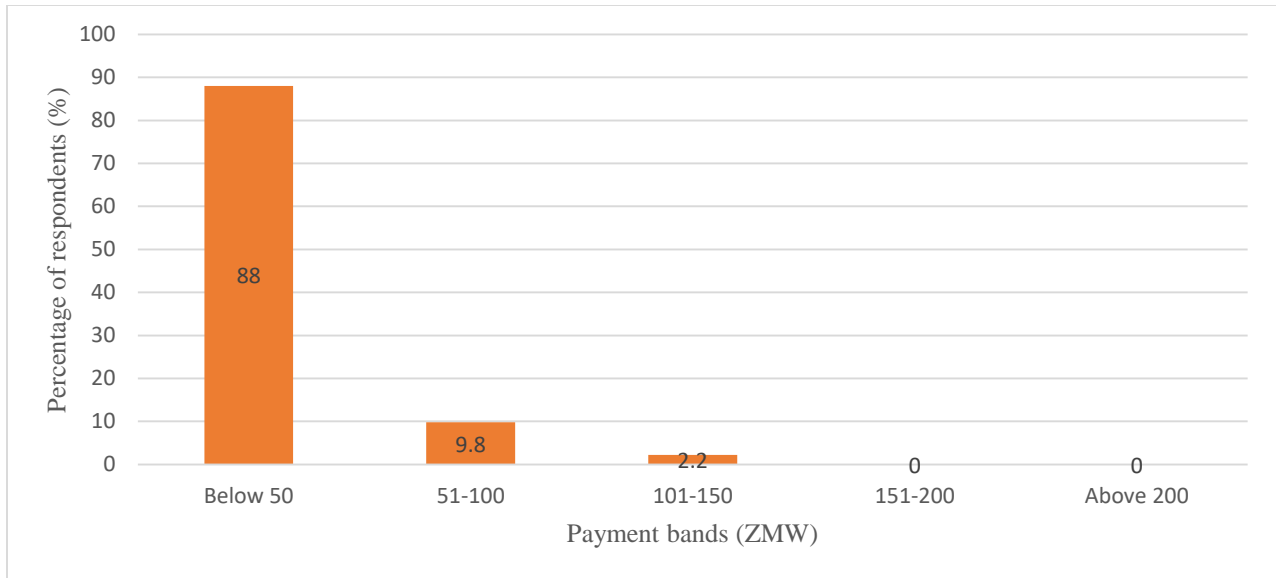


Figure 14: Payment band of Katamanda residents

The respondents were also asked to indicate the kind of expenditure which were typical for their families. Results are shown in Table 25.

Table 25: Katamanda residents typical family expenditure

| Family typical expenditure | Responses | Percentage |
|----------------------------|-----------|------------|
| Food | 80 | 48.2 |
| Groceries | 14 | 8.4 |
| School fees | 64 | 38.6 |
| Farm input | 8 | 4.8 |
| Energy | 0 | 0 |
| Total | 166 | 100.0 |

4.3.1.4 Sustainability assessment

A sustainable assessment is done here-under.

4.3.1.4.1 Monthly and Yearly revenues

Katamanda SMG supplies power to a total of 273 households, two (2) schools, one (1) rural health center and two (2) grocery shops and one (1) Liquor shop. From the 273 households the grid collected ZMW 3,276 per month and ZMW 120 was collected from the schools, RHC, Grocery shops and a

liquor shop giving a total of ZMW 3,276 + ZMW 120 = ZMW 3,396 (or USD 212.25 at current exchange rate of 1 USD = ZMW 16) at maximum collection. This gives a yearly revenue of USD 212.25 x 12 = USD 2,547 (ZMW 40,752), a highly insufficient amount even to manage operational expenditures of the plant resulting into the plant being financially unsustainable.

4.3.1.4.2 Operational costs

Estimated annual maintenance costs for the plant be financially sustainable is given in Table 26.

Table 26: Estimated annual maintenance cost for Katamanda SMG

| Number of components | Current replacement price (USD) | Price (ZMW) | Lifetime (years) | Annualized cost (USD) | Annualized cost (ZMW) |
|----------------------------|---------------------------------|-------------|------------------|-----------------------|-----------------------|
| 270x2V,150Ah Batteries | 92,340 | 1,477,440 | 5 | 18,468 | 295,488 |
| 1 x 50kW inverter | 2,312 | 36,992 | 10 | 231 | 3,699 |
| 2 x 100A Charge controller | 1,400 | 22,400 | 10 | 140 | 2,240 |
| Miscellaneous | | | | 125 | 2,000 |
| Sub-total | | | | 18,964 | 303,424 |

Adding the overhead costs calculated in Table 5 gives a total of USD 35,164 (ZMW 562,624), the minimum yearly revenue required to run the plant sustainably in terms of OPEX and overhead costs. From this amount of money, a sustainable tariff is estimated.

4.3.1.4.3 Sustainable tariff estimation

From Table 27, it's clear that the operation sustainable tariff is USD 0.40/kWh (or ZMW 6.42) which is above the ZESCO 2021 residential tariff of about ZMW 1.15 per unit for consumption ranging between 101 to 300 units. However, this is a lower tariff compared to that of Chibwika solar mini-grid. This is because Katamanda SMG operates at a larger capacity compared to Chibwika and the other three SMGs in this study.

Table 27: Annual energy generated and tariff estimation for Katamanda SMG

| Item | Size/Value |
|---|------------------------|
| Total System capacity (kWp). | 51.8 |
| Average solar irradiation in the area (kWh/m ² /day) | 5.786 |
| Energy generated daily (kWh). | 51.8 x 5.786 = 300 |
| Annual energy generation (kWh). | 300 x 365 = 109,500 |
| After 20% energy losses (kWh). | 109,500 x 0.8 = 87,600 |
| Annual energy sold 80% (kWh). | 87,600 |
| Sustainable Tariff (USD/ kWh). | 35,164/87,600 = 0.40 |

Assuming the plant is running at full capacity and the connected households increase to 300 without any subsidy apart from the 100% capital subsidy. The amount of money each household should pay per month to attain a sustainable tariff is calculated. The average cost per household to generate sufficient revenue to meet overhead and maintenance expenses = USD 35,164/300 households = USD 117 per household per annum or USD 9.77 (ZMW 156) per household per month. This amount is beyond the capability of Katamanda residents due to their low average yearly income resulting into low ability to pay for electricity. Worse, the residents' willingness to pay for electricity is also very low. The failure by some households to pay the current low fixed tariff structure of ZMW 12 per month is a clear indication of lack of willingness to pay. Katamanda SMG is therefore financially unsustainable.

4.3.2 Technical sustainability (configuration and specifications)

4.3.2.1 Solar PV modules

Table 28 and Table 29 Show the specification and configuration of the solar PV modules.

Table 28: Katamanda Solar PV module specification

| | |
|---|-----------------|
| Manufacturer | JA SOLAR |
| Model | JAP6-72-320/4BB |
| Number of modules | 162 |
| Voltage at P _{max} (V) | 37.38 |
| Current at P _{max} (A) | 8.56 |
| Module efficiency (%) | 17 |
| Power tolerance (%) | ± 3 |
| Temperature coefficient of V _m (%) | - 0.38/°C |

Table 29: Katamanda Solar PV module configuration

| | |
|------------------------------------|----------------------|
| Solar PV module orientation | North-East |
| Solar PV module inclination | 36 |
| Total number of solar PV modules | 162 |
| Number of PV modules in a string | 18 |
| Number of strings in parallel | 9 |
| String configuration | (1 x 18) x 9 strings |
| String voltage (V) | 672.84 |
| String current (A) | 8.56 |
| Maximum total charging current (A) | 77.04 |

4.3.2.2 Batteries

Most of the information on batteries was not found because the batteries were not labeled and no manual or information of the battery specifications was available at the SMG. However, the system consists of nine (9) strings connected in parallel. Information such as battery capacity was missing, therefore usable battery capacity at 50% DoD is not calculated. Table 30 summarizes the battery system specifications and configuration.

Table 30: Battery specification & configuration

| | |
|-----------------------------------|----------------|
| Technology | Not given |
| Manufacturer | Not given |
| Model | Not given |
| Total number of cells/batteries | 270 |
| Number of batteries in a string | 30 |
| Cell voltage (V) | 2 |
| String voltage (V) | 30 x 2 = 60 |
| Battery/cell capacity (Ah) | Not given |
| Total battery capacity (Ah) | Not given |
| Usable battery capacity @ 50% DoD | Not calculated |

4.3.2.3 Inverters and charge controllers

The inverter and charge controllers are embedded in one control system and no specifications was given as there were no data manuals and no technical personnel at the station with answers to these questions. Efforts were made to source for information from the installers (ETERN) and information was not provided.

4.3.3 Daily energy load in comparison with system size

Table 31 shows that the daily load energy consumption is 175.39 kWh which is far much less than the plants daily energy generation for sale of about 240 kWh giving energy surplus of 65 kWh oversizing the plant by 11 kW.

Table 31: Katamanda solar mini grid daily energy consumption table

| Devices | Quantity | Wattage (W) | Total wattage (W) | Operation hours | Energy (Wh) = total wattage x operation hours |
|--------------------|----------|-------------|-------------------|-----------------|---|
| Televisions | 32 | 100 | 3,200 | 10 | 32,000 |
| Satellite decoders | 15 | 21 | 315 | 10 | 3,150 |
| Fridges | 10 | 250 | 2,500 | 12 | 30,000 |
| Desktop Computers | 15 | 200 | 3,000 | 6 | 18,000 |
| Radios | 32 | 40 | 1,280 | 10 | 12,800 |
| Phone chargers | 40 | 6 | 240 | 6 | 1,440 |
| Bulbs | 520 | 15 | 7,800 | 10 | 78,000 |
| Total | | | | | 175,390 = 175.39 kWh |

4.3.4 Challenges

Some of the challenges of the mini-grid include; (a) lack of professionalism in the running of the plant as well as little technical capacity among the community to run this system efficiently; (b) the tariff is too low and fixed regardless of uses hence being deemed unfair for plant sustainability; (c) currently the residents do not see the need to pay for electricity as they believe it was just a gift to them and (d) seasonal income generation mostly from farming.

4.3.5 Remedies

Based on the above challenges, some of the remedies are; (a) The operation of the system should be given to a private company with clear terms of reference so that it runs like a business by competent and trained people; (b) Introduce the use of prepaid meters and impose a balanced tariff structure; (c) there is need of serious sensitization to residents about the use of solar electricity and its capability to generate income for maintenance and replacement cost of plants; and (d) encourage residents to do other businesses that can generate income on a daily, weekly and monthly basis rather than waiting

for yearly income from maize farming. This will help them raise their levels of income, and increase their ability and willingness to pay for solar power.

4.4 Magodi solar mini-grid

The SMG is 48 kWp in capacity, located in Chasefu district of Eastern Province at chief Magodi's palace. It was commissioned in March 2017 by National Technology Business Centre (NTBC) and was left to be run by the community. The plant is no longer operational. The SMG supplied power to a total 240 households and later reduced to 190 households, a nearby school and a Rural Health Centre. The SMG is shown in Figure 15.



Figure 15: Magodi solar mini-grid

4.4.1 Economic sustainability

The funding, cost of the plant, and financial sustainability is analyzed here-under.

4.4.1.1 Funding and cost of the plant

Magodi SMG was a donation to the community by the Norwegian Government and Danish Embassy, via National Technology Business Centre, and the capital expenditure (CAPEX) was not revealed to the researcher.

4.4.1.2 Tariff structure and business model

Just like the other two (2) community solar mini-grids studied, the grid management imposed a fixed monthly charge of ZMW 30 (USD 1.88) towards electricity payments. 240 households, one (1) School and one (1) Clinic were connected to the grid. The plant had no clear business model.

4.4.1.3: Socio economic profile (occupation, average yearly income, income spread, willingness to pay for electricity, and typical expenditure)

Table 32 shows the distribution of respondents by way of occupation. From the table, it is clear that the majority of the people interviewed were farmers representing 75.9% whereas the minority respondents were found to be civil servants represented by a score of 10.3% with 13.8% being business people.

Table 32: Magodi distribution of respondents by occupation

| Occupation | Respondents | Percentage |
|---------------------------|-------------|------------|
| Farmers | 44 | 75.9 |
| Fishermen | 0 | 0.0 |
| Businessmen/Businesswomen | 8 | 13.8 |
| Civil Servants | 6 | 10.3 |
| Total | 58 | 100.0 |

The average yearly income and income spread of Magodi residents is shown in Figure 16 and Figure 17.

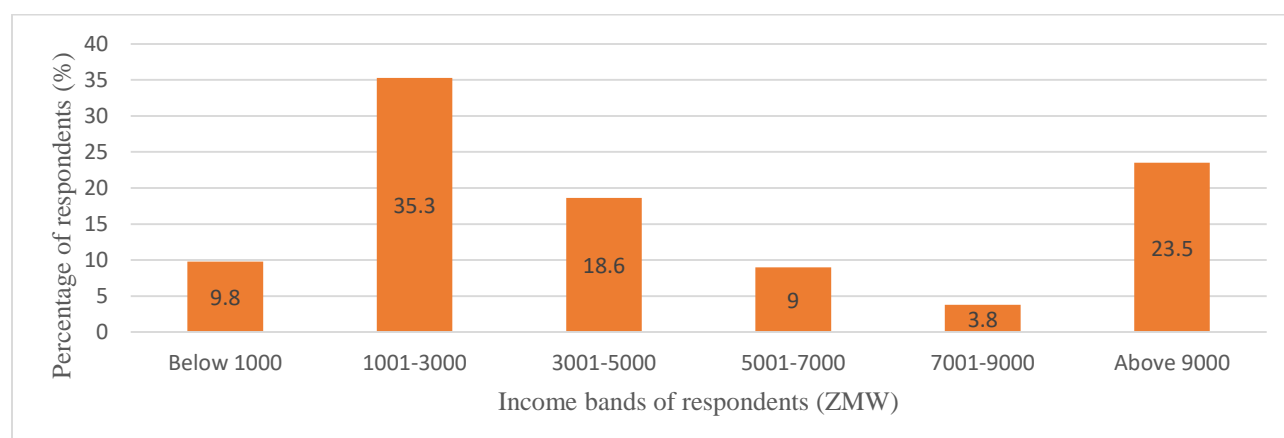


Figure 16: Average yearly income for Magodi residents

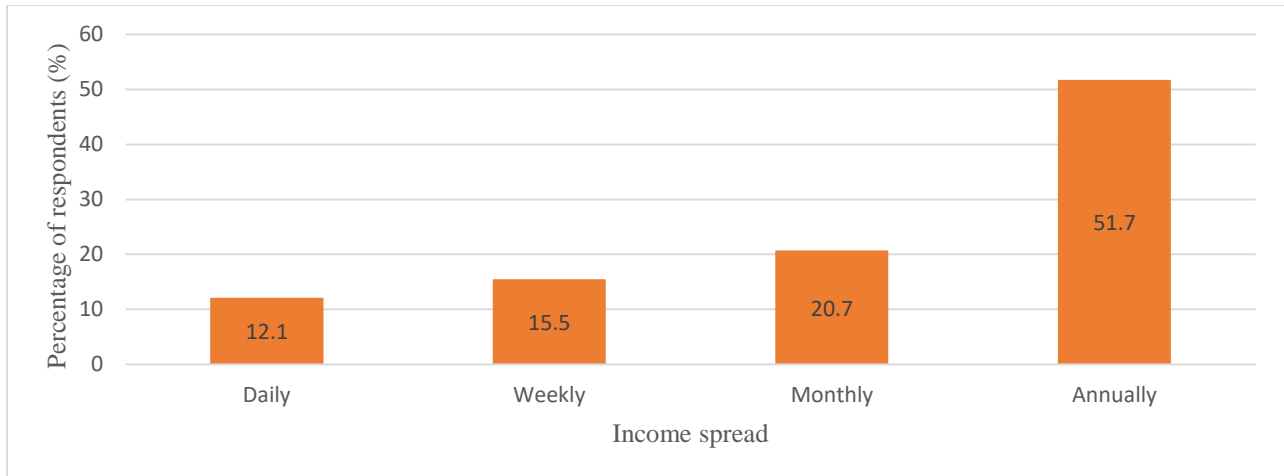


Figure 17: Income spread for Magodi residents

Table 33 shows the information on how families typically spend their earnings towards food, groceries, school fees, energy as well as farming inputs.

Table 33: Typical family expenditure for Magodi residents

| Family typical expenditure | Responses | Percentage |
|----------------------------|-----------|------------|
| Food | 41 | 29.5 |
| Groceries | 17 | 12.2 |
| School fees | 52 | 37.4 |
| Farm input | 19 | 13.7 |
| Energy | 10 | 7.2 |
| Total | 139 | 100.0 |

The willingness to pay for electricity by the residents is shown in Figure 18.

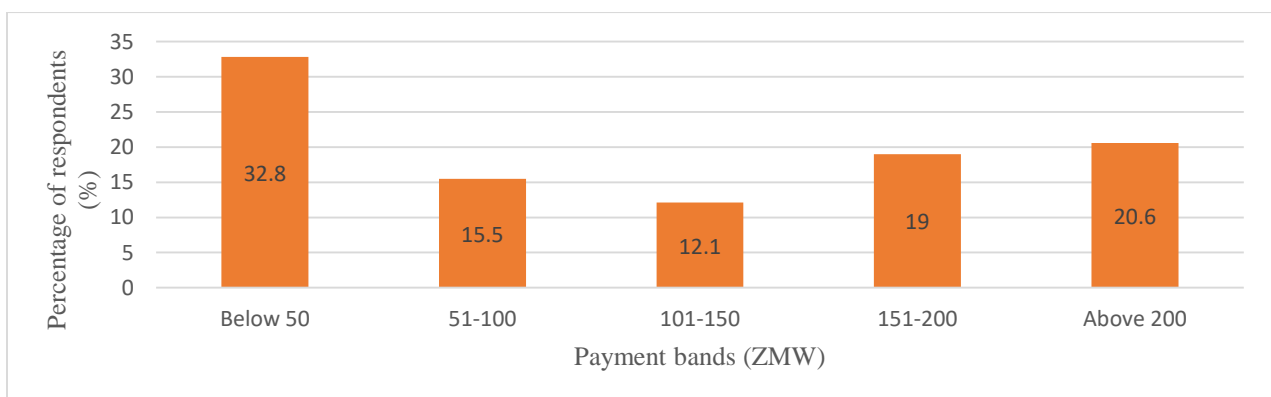


Figure 18: Amount of money Magodi residents were willing to pay for electricity per month

4.4.1.4 Sustainability assessment

4.4.1.4.1 Monthly and Yearly revenues

As earlier stated, Magodi has a total capacity of 48 kWp making it the second largest among the solar mini-grid under study. It was connected to a total of 240 households, one (1) school and one (1) rural health center. Each household used to pay a fixed charge of ZMW 30 (USD 1.88) per month with the school and RHC paying ZMW 50 each per month. A total amount of $240 \times \text{ZMW } 30 = \text{ZMW } 7,200$ plus ZMW 100 from the school and the RHC was generated per month at maximum collection. This yielded a yearly revenue of $\text{ZMW } 7,300 \times 12 = \text{ZMW } 87,600$ (USD 5,475). This amount is less than half of the annualized cost to cater for operational expenditures of the plant. This is the main reason that caused the plant to shut down, making it financially unsustainable.

4.3.1.4.2 Operational costs

Table 34 summarizes estimated annual maintenance costs for the plant to run financially sustainable.

Table 34: Estimated annual maintenance cost for Magodi SMG

| Number of components | Current replacement price (USD) | Price (ZMW) | Lifetime (years) | Annualized cost (USD) | Annualized cost (ZMW) |
|-----------------------------|---------------------------------|-------------|------------------|-----------------------|-----------------------|
| Batteries(480x2V,600Ah) | 113,760 | 1,820,160 | 5 | 22,752 | 364,032 |
| Inverters (4 x 12kW) | 7,000 | 112,000 | 10 | 700 | 11,200 |
| Charge controllers (4x100A) | 2,800 | 44,800 | 10 | 280 | 4,480 |
| Miscellaneous | | | | 125 | 2,000 |
| Sub-total | | | | 23,857 | 381,712 |

A total of USD 40,057 (ZMW 640,912) is the minimum money required to be generated by the plant every year for it to cutter for operational expenditures and overhead costs.

4.4.1.4.3 Sustainable tariff estimation

Calculations on tariff estimation are done as shown in Table 35, it is clear that the operation sustainable tariff is USD 0.5/kWh (or ZMW 8.00). Similarly, this rate is too high compared to that of ZESCO 2021 residential tariff of about ZMW 1.15 per unit for consumption ranging between 101 to

300 units. However, USD 0.5/kWh is slightly a lower tariff compared to that of Chibwika solar mini-grid which stands at USD 0.57/kWh.

Table 35: Annual energy generated and tariff estimation for Magodi SMG

| Item | Size/Value |
|---|------------------------------|
| Total System capacity (kWp). | 48 |
| Average solar irradiation in the area (kWh/m ² /day) | 5.694 |
| Energy generated daily (kWh). | $48 \times 5.694 = 273$ |
| Annual energy generation (kWh). | $273 \times 365 = 99,645$ |
| After 20% energy losses (kWh). | $99,645 \times 0.8 = 79,716$ |
| Annual energy sold 80% (kWh). | 79,716 |
| Sustainable Tariff (USD/kWh). | $40,057/79,716 = 0.50$ |

Assuming the plant is revamped and starts operating at full capacity, with the 240 households, a school and a clinic to represent 10 households will result in the plant supplying power to 250 households. With no subsidy apart from the 100% capital subsidy, the amount of money each household can pay to attain a sustainable tariff is USD 40,057/250 households = USD 160 per household per annum, or USD 13 (ZMW 208) per month. This average cost per household is sufficient to generate revenue to meet overhead and maintenance expenses. The ability and willingness to pay for electricity in the area is very low i.e. majority of the residents were not willing to pay an amount above ZMW 50. The low yearly average income and poor income spread contributed to the shutdown of the solar mini-grid as it was financially unsustainable.

4.4.2 Technical sustainability (configuration and specifications)

4.4.2.1 Solar PV modules

The PV modules were identified in different lines from the powerhouse. Line A being the closest with 7 sub arrays per line yielding 56 PV modules with installed capacity of 11,200 Wp. Line B comprises 8 strings with 8 solar panels each giving a capacity of 12,800Wp. Line C is exactly the same as line B. Line D is the furthest from the power house and has the same connections as line A. It is important to note that each sub array was reconfigured to sit as stand-alone unit with the 8 PV modules connected in series which were then connected in parallel pairs to feed into the charge controllers through the termination junction box. The information is summarized in Tables 36 and 37.

Table 36: Magodi Solar PV module specification

| | |
|---|------------------------|
| Manufacturer | African Energy |
| Model | AFR-200 |
| Number of modules | 240@ 200W _p |
| Voltage at P _{max} (V) | 37.77 |
| Current at P _{max} (A) | 5.29 |
| Module efficiency (%) | 14.88 |
| Power tolerance (%) | ± 3 |
| Temperature coefficient of V _m (%) | - 0.38/°C |

Table 37: Magodi Solar PV module configuration

| | |
|------------------------------------|--------|
| Solar PV module orientation | North |
| Solar PV module inclination | 18 |
| Total number of solar PV modules | 240 |
| Number of PV modules in a string | 8 |
| Number of strings in parallel | 30 |
| String voltage (V) | 302.16 |
| String current (A) | 5.29 |
| Maximum total charging current (A) | 158.7 |

4.4.2.2 Batteries

The system had four strings of batteries which was shared by the 4 PV lines. The specifications and configuration of the batteries is shown in Table 38.

Table 38: Magodi Battery Specification & configuration

| | |
|-----------------------------------|------------------------|
| Technology | Lead acid, open vented |
| Manufacturer | Not given |
| Model | Not given |
| Total number of cells/batteries | 480 |
| Number of batteries in a string | 120 |
| Cell voltage (V) | 2 |
| String voltage (V) | 240 |
| Battery/cell capacity (Ah) | 600 |
| Total battery capacity (Ah) | 2,400 |
| Usable battery capacity @ 50% DoD | 1,200 |

4.4.2.3 Inverters and charge controllers

The system consisted of 4 PWM single phase inverters rated 12 kW with total rated power of 48 kW. Each inverter was connected to an individual PV sub array line which implies that when one inverter has a fault, the specific line connected to that inverter will be load shaded. In a similar manner the 4 charge controllers rated 100A each were connected to control charging and discharging of batteries for a specific string. The information is summarized in Tables 39 and 40.

Table 39: Magodi SMG inverter specification

| | |
|---------------------------|---------------|
| Manufacturer | Not given |
| Model | Not given |
| Technology | PWM |
| Phase type | Single |
| Total number of inverters | 4 |
| Rated power (kW) | 12 |
| Total rated power (kW) | 48 |
| Protection type | Not protected |

Table 40: Magodi SMG charge controller specifications

| | |
|------------------------------------|-----------|
| Manufacturer | Not given |
| Model | Not given |
| Technology | PWM |
| Total number of charge Controllers | 4 |
| Charge controller rating (A) | 100 |
| Total Charge controller rating (A) | 400 |

4.4.3 Daily energy load in comparison with system size

With respect to the daily energy generated by the solar mini-grid of $48 \times 5.694 = 273$ kWh and energy available for sale of 218 kWh. The load requirement of 141.24 kWh calculated from Table 41 shows that the plant was oversized by 14 kW resulting in daily energy surplus of 77 kWh.

Table 41: Magodi solar mini grid daily energy consumption table

| Devices | Quantity | Wattage(W) | Total wattage (W) | Operation hours | Energy(Wh)=total wattage x operation hours |
|--------------------|----------|------------|-------------------|-----------------|--|
| Televisions | 38 | 96 | 3,648 | 10 | 36,480 |
| Satellite decoders | 20 | 21 | 420 | 10 | 4,200 |
| Fridges | 12 | 250 | 3,000 | 12 | 36,000 |
| Desktop Computers | 10 | 200 | 2,000 | 6 | 12,000 |
| Radios | 27 | 40 | 1,080 | 10 | 10,800 |
| Phone chargers | 35 | 6 | 210 | 6 | 1,260 |
| Bulbs | 405 | 10 | 4,050 | 10 | 40,500 |
| Total | | | | | 141,240=141.24 kWh |

4.4.4 Challenges

Some of the challenges of the defunct Magodi SMG include; (a) poor system configuration of the battery bank which got damaged; (b) the system was not protected from lightning, there were no surge arrestors and circuit breakers, resulting in the plant suffering multiple lightning strikes, hence destroying inverters and charge controllers; and (c) low and fixed tariff structure coupled with low willingness and ability to pay due to seasonal income generation.

4.4.5 Remedies

The remedies to the above challenges include; (a) the plant may require a clear business model that will be able to generate income to replace technical components when need arises; (b) reconfigure the whole system, buy new batteries, inverters, charge controllers. Protect it from lightning via the use of surge arrestors and maintain the plant well to improve sustainability; and (c) Introduce prepaid meters and encourage the community to venture into other businesses of income generation.

4.5 Sinda solar mini-grid

The SMG is 24.4 kWp in capacity and is located in Sinda district of Eastern Province at Sinda village. The plant was commissioned in 2017 and is managed by Muhanya solar, a local private company. The SMG is operational. The company's initial plan was to supply power to a total number of 300 households though only 60 households were connected and later by September 2020 only 40

households were still connected. The failure of the batteries to store energy for use at night led to a number of clients to default in paying for electricity and later got disconnected. It also supplied power to a nearby school and five businesses which included grocery shops, and barber shops. Figure 19 shows the SMG.



Figure 19: Sinda solar mini-grid

4.5.1 Economic Sustainability

4.5.1.1 Funding and cost of the plant

The solar mini-grid is privately owned by Muhanya Solar Limited and was funded by United States African Development Foundation (USADF) in partnership with power Africa at a cost of USD 100,000 in form of a grant [43].

4.5.1.2 Tariff structure and business model

The tariff structure of Sinda solar mini-grid is a fixed charge of ZMW 5.00 (USD 0.31) every 24 hours of power availability but irrespective of the amount of power used. This simply means whenever there is power cut, there are no charges at that particular point. Assuming there is power 24/7, the connected households would pay ZMW 150 (USD 9.38) per month. However, this does not happen because the plant is very inconsistent in the supply of power. As at the time of the study, the

clients complained that the maximum number of hours they have power in a day is just six (6). This means the plant makes losses as ZMW 5 (USD 0.31) would last for about 24 hours/6 hours = 4 days resulting in generating about ZMW 40 (USD 2.50) per month, only 26% of what they would generate if the plant supplied power 24/7. The plant is not run professionally and lacks a clear business model.

4.4.1.3 Socio economic profile (occupation, average yearly income, income spread, willingness to pay for electricity, and typical expenditure)

Table 42 shows the distribution of respondents by occupation.

Table 42: Sinda distribution of respondents by occupation

| Occupation | Respondents | Percentage |
|---------------------------|-------------|------------|
| Farmers | 32 | 62.7 |
| Fishermen | 0 | 0.0 |
| Businessmen/Businesswomen | 15 | 29.5 |
| Civil Servants | 4 | 7.8 |
| Total | 51 | 100.0 |

The major source of income for the community in Sinda district is farming, results on average yearly income was also collected and is presented in Figures 20 and 21.



Figure 20: Average yearly income of Sinda residents

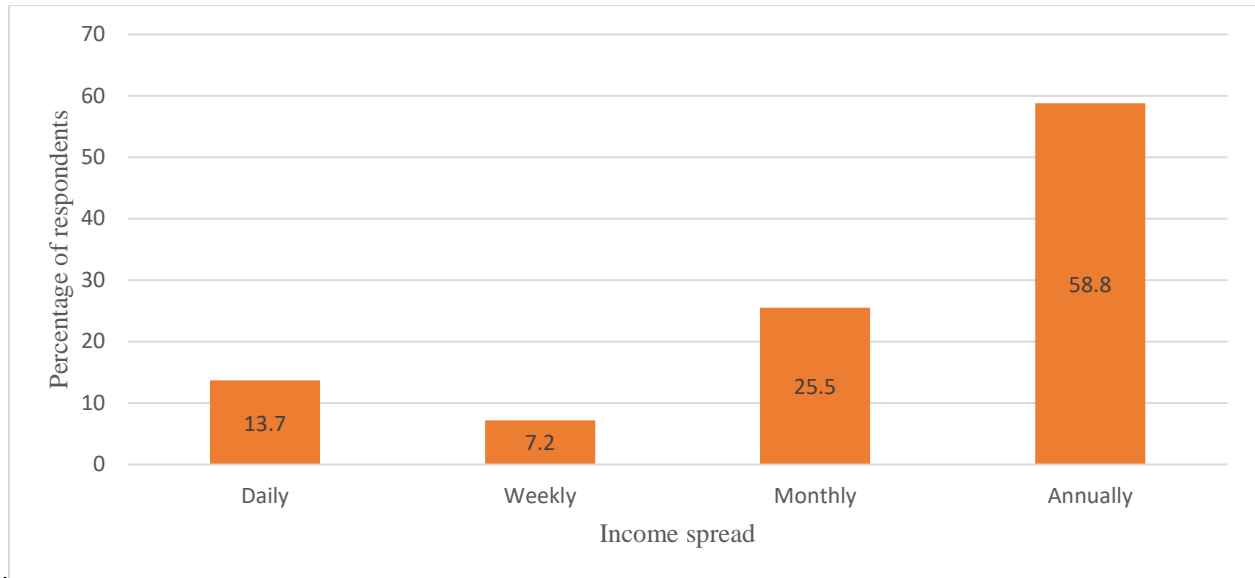


Figure 21: Income spread for Sinda residents

Table 43 shows family's typical expenditure of their earnings.

Table 43: Sinda resident's typical family expenditure

| Family typical expenditure | Responses | Percentage |
|----------------------------|-----------|------------|
| Food | 37 | 29.6 |
| Groceries | 13 | 10.4 |
| School fees | 41 | 32.8 |
| Farm input | 11 | 8.8 |
| Energy | 23 | 18.4 |
| Total | 125 | 100.0 |

Figure 22 shows the amount of money Sinda residents were willing to pay for electricity.

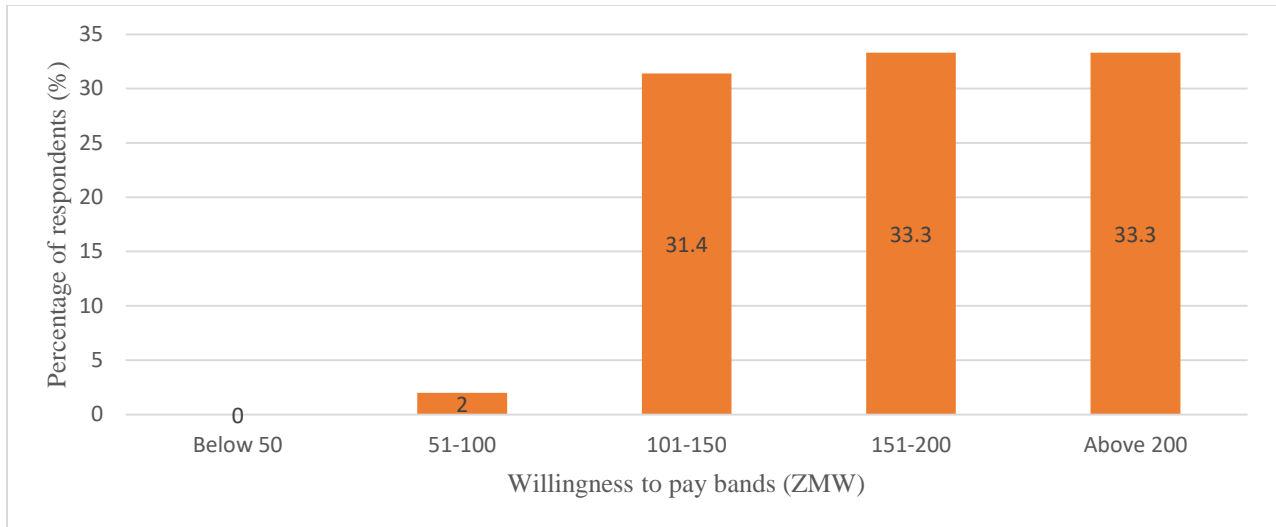


Figure 22: Amount of money Sinda residents were willing to pay for electricity per month

4.5.1.4 Sustainability assessment

Like the other four (4) solar mini-grids studied, we look at monthly and yearly revenues, operational costs and salaries for workers. This will guide in coming up with a sustainable tariff.

4.5.1.4.1 Monthly and yearly revenues

As stated earlier, Sinda solar mini-grid had an initial plan of supplying power to about 300 households. However, from its implementation the plant supplied power to only 60 households which later reduced to 40 households by the year 2020 the time of this study. The reason as to why the mini-grid owner did not connect the initial planned 300 households is not known., however, on a technical point of view a 24.4 kWp system is too small to power a total of 300 households. The monthly and yearly revenue collection is calculated based on the initial 60 households connected to the plant. From the tariff structure, each household paid a maximum of ZMW 150 per month, implying that the plant collected a total of $ZMW 150 \times 60 = ZMW 9000$ per month at 24/7 power supply. A total amount of $ZMW 9,000 \times 12 = ZMW 108,000$ [(or USD 6,750) at 1 USD = ZMW 16] was generated per year. This implies that it would take about 15 years for the plant to reach the breakeven point, in this scenario there are no operational costs and salaries paid from the income generated. This is not possible due to the fact that the solar panel lifespan is about 25 to 30 years, with inverters, charge controllers and batteries at 10 years, 10 years and 5 years respectively. If the initial 300 households

were connected to the plant and the plant operated at full capacity, Muhanya solar would make yearly revenue equal to ZMW 540,000 (USD 33,750) and this would reach the breakeven cost in 3 years. However, the SMG is too small to supply power to 300 households but can supply to a total number of 150 households, this extends the breakeven period to 6 years. With the current reduction in operation hours and number of households connected to the plant, the plant is currently highly unsustainable. Financial sustainability of the plant is looked at in terms of OPEX and overhead costs not CAPEX because funding was in form of grant.

4.5.1.4.2 Operational costs

Refer to Table 44 for estimated annual maintenance costs of the plant. A total of USD 23,486 (ZMW 375,776) is the minimum amount of money required to be generated by the plant every year in order to cutter for operational expenditures and overhead cost.

Table 44: Estimated annual maintenance cost for Sinda SMG

| Number of components | Total Replacement price (USD) | Price (ZMW) | Lifetime (years) | Annualized cost (USD) | Annualized cost (ZMW) |
|-----------------------------|--------------------------------------|--------------------|-------------------------|------------------------------|------------------------------|
| Batteries(24 6V,556Ah) | 32,904 | 526,464 | 5 | 6,581 | 105,296 |
| Inverters (3x6.8kVA) | 3,000 | 48,000 | 10 | 300 | 4,800 |
| Charge controllers (4x140A) | 2,800 | 44,800 | 10 | 280 | 4,480 |
| Miscellaneous | | | | 125 | 2,000 |
| Sub-total | | | | 7,286 | 116,576 |

4.5.1.4.3 Sustainable tariff estimation

Table 45 below shows calculations on tariff estimation. The operationally sustainable tariff of USD 0.56/kWh (about ZMW 9.00/kWh) is too high compared to the prevailing 2021 ZESCO residential tariff of USD 0.072/kWh (ZMW 1.15/kWh).

Table 45: Annual energy generated and tariff estimation for Sinda SMG

| Item | Size/Value |
|--|-----------------------|
| Total System capacity (kWp). | 24.4 |
| Average solar irradiation in the area (kWh/m ² /day). | 5.875 |
| Energy generated daily (kWh). | 24.4 x 5.875 = 143 |
| Annual energy generation (kWh). | 143 x 365 = 52,195 |
| After 20% energy losses (kWh). | 52,195 x 0.8 = 41,756 |
| Annual energy sold 80% (kWh). | 41,756 |
| Sustainable tariff (USD/ kWh). | 23,486 /41,756 = 0.56 |

Assuming the plant operates at full capacity and the connected households increase to 150, without any subsidy apart from the 100% capital subsidy the amount of money each household can pay to attain a sustainable tariff is USD 23,486/150 households = USD 157/household (or ZMW 2,512/household) per year or USD 13.10 (ZMW 210) per month. The current power cuts and reduced number of households connected the SMG makes the project financially unsustainable.

4.5.2 Technical sustainability (configuration and specifications)

4.5.2.1 Solar PV modules

The information for specifications and configuration of the solar PV modules is given in Tables 46 and 47.

Table 46: Sinda solar PV module specification

| | |
|---|---------------|
| Manufacturer | SUNTECH |
| Model | STP305-24/Vem |
| Number of modules | 80 |
| Voltage at P _{max} (V) | 36.2 |
| Current at P _{max} (A) | 8.43 |
| Module efficiency (%) | 17 |
| Power tolerance (%) | 0/+5%. |
| Temperature coefficient of V _m (%) | - 0.38/ °C |

Table 47: Sinda solar PV module configuration

| | |
|------------------------------------|----------------------|
| Solar PV module orientation | North |
| Solar PV module inclination | 20 |
| Total number of solar PV modules | 80 |
| Number of PV modules in a string | 4 |
| Number of strings in parallel | 20 |
| String configuration | (1 x 4) x 20 strings |
| String voltage (V) | 144.8 |
| String current (A) | 8.43 |
| Maximum total charging current (A) | 168.6 |

4.5.2.2 Batteries

The battery specifications and configuration of the SMG is shown in Table 48.

Table 48: Sinda SMG battery specification & configuration

| | |
|-----------------------------------|-----------------------------|
| Technology | Flooded |
| Manufacturer | Surrete Battery Company Ltd |
| Model | S-556 |
| Total number of cells/batteries | 24 |
| Number of batteries in a string | 8 |
| Cell voltage (V) | 6 |
| String voltage (V) | 48 |
| Battery/cell capacity (Ah) | 556 |
| Total battery capacity (Ah) | 3 x 556=1,668 |
| Usable battery capacity @ 50% DoD | 834 |

4.5.2.3 Inverters and Charge controllers

The inverters and charge controllers specification is given in Tables 49 and 50.

Table 49: Sinda SMG inverter specification

| | |
|---------------------------|--------------------|
| Manufacturer | Schneider Electric |
| Model | XW 8548 E |
| Technology | Not Given |
| Phase type | 3 |
| Total number of inverters | 3 |
| Rated power (kVA) | 6.8 |
| Total rated power (kVA) | 20.4 |
| Protection type | Not given |

Table 50: Sinda SMG charge controller specifications

| | |
|------------------------------------|--------------------|
| Manufacturer | Schneider Electric |
| Model | Magnum PT 100 |
| Technology | MPPT |
| Total number of charge Controllers | 4 |
| Charge controller rating (A) | 140 |
| Total Charge controller rating (A) | 4 x 140 = 560 |

4.5.3 Daily energy load in comparison with system size

Table 51 indicates that the energy load requirement currently is 112.13 kWh which is less than the energy generation of 143 kWh but almost equal to 114 kWh daily energy available for sale. The system is currently neither oversized nor undersized. However, the energy consumption table does not depict the initial energy consumption of the community because currently most customers are disconnected due to the plant's failure to supply electricity 24/7.

Table 51: Sinda solar mini-grid daily energy consumption table

| Device | Quantity | Wattage (W) | Total wattage (W) | Operation hours | Energy(Wh)=Total wattage x operation hours. |
|-------------------|----------|-------------|-------------------|-----------------|---|
| Television | 30 | 100 | 3,000 | 10 | 30,000 |
| Satellite decoder | 15 | 21 | 315 | 10 | 3,150 |
| Fridge | 8 | 250 | 2,000 | 12 | 24,000 |
| Desktop computer | 7 | 200 | 1,400 | 6 | 8,400 |
| Radio | 20 | 40 | 800 | 10 | 8,000 |
| Phone charger | 30 | 6 | 180 | 6 | 1,080 |
| Bulb | 250 | 15 | 3,750 | 10 | 37,500 |
| Total | | | | | 112,130=112.13 kWh |

4.5.4 Challenges

The challenges for the Sinda SMG include; (a) frequent downtimes and not operating at full capacity due worn out batteries; (b) lack of technical expert on the ground to manage the plant; and (c) it appears that the private company has lost interest in maintaining and running the plant.

4.5.5 Remedies

Redress to these challenges would include; (a) replacing the worn out batteries and supply power to the satisfaction of the clients; (b) train qualified technical experts to be at the site to operate the plant, and; (c) Muhanya solar company that runs the Sinda SMG should take interest and get to the bottom of the problem or sell the SMG to people that can run it effectively.

CHAPTER 5

5.0 DISCUSSION

This chapter discusses the social and environmental sustainability as well as tariff structure and overall sustainability of the five (5) solar mini-grids in the study.

5.1 Social sustainability

All the five (5) SMGs have similar impacts on social sustainability. Social sustainability in this case implies having an affordable and fair tariff plan, client satisfaction, availability of electricity for 24/7. Except for Chitandika and Sinda SMGS, the three other mini-grids are donations. Consultations on site location were done and go ahead for constructions was given by the traditional leaders of the lands, such as chiefs, headmen and others. Meetings with the communities to understand their energy needs were held only by Chitandika SMG among the five (5) SMGs. Chibwika, Katamanda and Magodi were donations and after construction, they were left to be run by the community who believed they were gifts and therefore no need to pay for electricity. Communities did not understand the need for component replacement when exceeding their lifespan. This resulted in poor fixed tariff structures, leading to financial unsustainability of the plants. In terms of supply the mini-grids are able to supply electricity 24/7 to the customer's satisfaction except for Sinda and Magodi which have technical problems.

Despite social challenges, results indicate improvements in the wellbeing of the communities in terms of education delivery, health delivery, crime prevalence reduction, extended business hours, and entertainment among others.

In terms of education, the implementation of the solar plants has increased access to study materials as learners are able to charge their phones for research purposes, some rural schools are now able to use school computers for easy lesson delivery on computer studies. The availability of light even at night has extended the study hours of the learners thereby improving the results.

Health delivery has also been improved, RHCs are now connected to solar which has made it easier for health workers to give services even at night. The reduction in the use of kerosene due to availability of solar light has also reduced eye problems, respiratory problems and other diseases that

arise due to exposure to kerosene. There is a further increase in safety at night as one of the mothers indicated that she can sleep better as she easily checks if her baby is sleeping safely next to her without fear of darkness.

The presence of light also reduced crime prevalence. People with business are happy with the implementation of SMGs as this has extended their business hours. Further, households surveyed reported a sense of connectedness with the outside world and within the community. The availability of entertainment such as watching soccer via TVs has brought the community together and has connected them to the outside world. The community are able to watch TV news and are socially updated to what is happening in the country and world at large. Even though a lot has to be done to improve the social sustainability of SMGs, the study reveals that the five (5) solar mini-grids are socially sustainable.

5.2 Environmental sustainability

Findings revealed that all SMG had similar environmental impacts on the communities. This was based on the uses of energy for lighting, cooking and heating before and after the implementation of the studied solar mini-grids. The use of diesel in generators and hammer mills was also taken into consideration. Studies have revealed that pollution from kerosene lamps and candles used for lighting by rural households contributes to greenhouse gas (GHG) emissions. Further, studies show that, for every litre of kerosene burnt, 2.5 kg of CO₂ are released into the atmosphere [44]. In correlation to other studies, data revealed a consumption of about 0.1 litres of kerosene per household on a daily basis. In addition to emissions of CO₂, kerosene lamps produce black carbon during combustion, increasing their contribution to GHGs considerably [45]. Studies also indicate that about 2.7 kg of CO₂ is produced from burning just 1 litre of diesel [46].

Energy sources for lighting before and after the implementation of the SMGs in the areas sampled is given in Tables 52 and 53 respectively.

Table 52: Sources of energy for lighting before implementation of solar mini-grids

| Energy source | Sampled households | Respondents | Percentage |
|--------------------|--------------------|-------------|------------|
| Kerosene/Candle | 314 | 140 | 44.6 |
| Battery lamp/Torch | 314 | 109 | 34.7 |
| Own solar lanterns | 314 | 65 | 20.7 |

Out of the 314 households sampled from five (5) SMG, 140 households representing 44.6% used Kerosene and candles for lighting. This implies that 44.6% of the households contributed massively to GHGs. 109 households and 65 households used battery lamp/torches and own solar lanterns representing 34.7% and 20.7% respectively.

The 140 households on average emitted about 12,775 kg or 12.775 tonnes of CO₂ every year. (i.e. every household used on average about 0.1 litres of kerosene every day, implying the 140 households on average used 140 x 0.1 litres = 14 litres of kerosene per day equivalent to 14 x 2.5 kg = 35 kg of CO₂ was emitted to the environment translating into 12,775 kg or 12.775 tonnes annually). According to the Global Carbon Project, the annual carbon emission of the year 2020 was about 35 billion tonnes [47] implying that just the 140 households studied contributed about 12.775 tonnes of the annual global CO₂ emission. This number looks very small, however, with respect to the sample size, this has a massive contribution to the amount of CO₂ produced on a global scale. In addition, liquid kerosene fuel potentially poses health risks prior to the combustion process as opposed to biomass fuels. Further, hazards such as fires, explosions and poisonings induced by kerosene are possible [48] [49].

Table 53: Sources of energy for lighting after implementation of solar mini grids

| Energy source | Sampled households | Respondents | Percentage |
|--------------------|--------------------|-------------|------------|
| Kerosene/Candle | 314 | 11 | 3.5 |
| Battery lamp/Torch | 314 | 56 | 17.8 |
| Own solar lanterns | 314 | 26 | 8.3 |
| Solar mini-grid | 314 | 221 | 70.4 |

In the same vein, results in Table 53 show a tremendous reduction (92%) in the use of kerosene and candles for lighting after the solar mini-grids were implemented. This value would have reduced to zero (0) had it not been for Magodi and Sinda solar mini-grids that are not working to maximum capacity resulting into some households returning to the old use of battery lamp/torch, kerosene/candle and own solar lanterns for lighting. With a 92% reduction in the use of kerosene and candles after SMGs implementation, GHGs emissions are also reduced to 1.004 tonnes annually.

Kerosene/candle use is now at 3.5%, battery lamp/torch at 17.8%, own solar lanterns at 8.3% and the majority 70.4% uses SMGs as a source of energy for lighting. This is a clear indication that SMGs helps in the reduction of carbon emissions to the environment. Apart from carbon emissions,

reduction in the number of households using kerosene due to the use of solar lighting has a lot of health benefits such as reducing the risks of suffering from diseases like cancer and asthma. Further studies reveal that the use of solar energy for lighting leads to better lighting quality, providing a pleasant environment for working, studying and improve indoor air quality at home [50]. Based on the small capacity of the five (5) SMG projects, users were not permitted to use heating appliances such as electric iron, electric stoves and water boilers. Consequently, none of the projects has led to reduction in the rate of deforestation, air pollution from traditional fuel sources and the workload of fetching firewood for cooking. However, at Chitandika SMG, there is a reduction in the use of diesel to run hammer mills and generators to power welding machines, barbershops, Saloons etc. This simply means, the substitute of diesel by solar power in the area has reduced the emission of GHGs from the burning of diesel. The study further revealed that before the implementation of the SMGs, to run these machines via the use of generators and diesel hammer mills, a minimum 30 litres of diesel for the population of Chitandika was used on a daily basis powering machines to do such activities. This contributed about 81kg of CO₂ to the environment translating to 29,565 kg every year. Thus, the implementation of Chitandika SMG in the area has led to a reduction in carbon emission to the environment.

It is important to note that small land clearing and use of certain diesel machines during the construction of the solar mini-grids may lead to air pollution just for the period of construction, However, the benefits of solar energy to the environment outweighs the pollution and land deforestation caused during construction period. The use of solar energy via SMGs is environmentally sustainable.

5.3 Tariff structure and analysis for the five (5) solar mini-grids

A financially viable solar mini-grid will balance financial incentives/subsidies and revenue streams from tariffs with debt, equity, and operational expenses both in the short and long term [51]. However, this does not necessarily mean that the funds needed must all come from consumer tariff payments. Some mini-grid are dependent on support from local or national governments to supply the funds needed to cover the operation and maintenance costs of the mini-grids. However, the operation plans for mini-grids which are dependent on government funding should consider the risk of political shifts which may affect the future availability of subsidies for the mini-grids [52] [53].

Tariff designs can be varied and should always be adapted to the specific circumstances of each individual mini-grid. Usually tariffs have two basic components, a connection fee and a service fee (often paid monthly) [54]. Connection fees are used to cover the connection costs incurred by the mini-grid operator. This fee can also be used as a measure to ensure a high level of commitment from the electricity consumers. In this way, connection fees can help increase the economic viability of the mini-grid, by covering part of the capital cost. It is important to note that, consumers who have paid an initial connection fee are likely to be willing to ensure that the mini-grid remains operational for a long period. Therefore, they might be willing to pay usage or service fees which cover the operation and maintenance costs for the grid [55] [56].

Tables 54 and 55 summarize annual revenue, and total annual costs as well as current and sustainable tariff structures of the five (5) solar mini-grids.

Table 54: Annual revenue and total annual cost of the SMGs

| Solar mini-grid | Annual revenue (USD) | Annual maintenance (USD) | Annual overhead costs (USD) | Total annual costs (USD) |
|------------------------|-----------------------------|---------------------------------|------------------------------------|---------------------------------|
| Chibwika | 4,200 | 14,784 | 16,200 | 30,984 |
| Chitandika | 8,213 | 4,525 | 16,200 | 20,725 |
| Katamanda | 2,547 | 18,964 | 16,200 | 35,164 |
| Magodi | 5,475 | 23,857 | 16,200 | 40,057 |
| Sinda | 6,750 | 7,286 | 16,200 | 23,486 |

It is clear from Table 54 that the annual revenue for the plants are far much less than the total annual cost. It is important to note that for the 24.4 kWp and 28.35 kWp SMGs, the annual maintenance cost is less compared to the other SMGs, however the overhead costs increased the total annual costs which increased their sustainable tariff structures. This clearly tells that in terms of maintenance cost it is expensive to run a small solar power plant than a large power plant because the overhead costs are almost the same in both cases.

Table 55: Economic sustainability of the five (5) solar mini-grids

| Solar mini-grid | Ownership | Tariff type | Current tariff price per Household (USD) | Sustainable tariff (USD) | Subsidized (Yes/No) |
|-----------------|-----------|-------------|--|--------------------------|---------------------|
| Chibwika | Community | Fixed | (3.13 to 6.25)/month | 0.57/kWh | No |
| Chitandika | Private | Prepaid | (0.38 to 1.13)/kWh | 0.43/kWh | No |
| Katamanda | Community | Fixed | (0.75 to 1.25)/month | 0.40/kWh | No |
| Magodi | Community | Fixed | 1.88/month | 0.50/kWh | No |
| Sinda | Private | Prepaid | 0.31/day | 0.56/kWh | No |

Table 55 shows that the five (5) solar mini-grids studied have different tariff structures. The current tariff structures are very low to sustain financially especially for the community owned SMGs. The sustainable tariff to cover at least maintenance and overhead costs ranges between USD 0.40/kWh and USD 0.57/kWh. The calculations indicated that the factors that affect the tariff structure are number of households connected to the SMG and its size (capacity). The bigger the plant and the more number of households connected to the grid, the lower the tariff structure to attain sustainability. Results revealed that due to the smaller capacity and lack of subsidies in the solar mini-grids, their sustainable tariff structure are far much high as compared to those from utility scales.

The study further revealed that consumers usually do not like high fixed costs and prefer tariffs based on their actual energy usage, since this allows them to be more financially flexible. Therefore, the economic viability of the mini-grid depends on selling a certain minimum amount of electricity (kWh) every year. More electricity sold results in higher profits for the mini-grid operator. The financial risk for the mini-grid operator is lowest if the tariff is composed of a fixed basic tariff element, which is high enough to cover the O&M costs. The disadvantage of fixed tariffs, however, is that they provide no incentive for the consumer to use electricity efficiently [45]. In this study, the community owned mini-grid consumers were very comfortable with their low fixed tariff due to lack of sensitization on the O&M costs. Those from private owned complained of expensive tariff structure. Therefore, there is need to strike a balance in tariff structure to favors both sustainability of the plant and the consumers of electricity.

5.4 Overall sustainability

Table 56 indicates the level of sustainability among the SMGs studied. It is clear that none of the solar mini-grid is financially sustainable, however Chibwika, Chitandika, and Katamanda were found to be technically, environmentally, and socially sustainable.

Table 56: Overall sustainability of the five (5) solar mini-grids

| Solar mini-grid | Economically sustainable | Technically sustainable | Environmentally sustainable | Socially sustainable |
|------------------------|---------------------------------|--------------------------------|------------------------------------|-----------------------------|
| Chibwika | No | Yes | Yes | Yes |
| Chitandika | No | Yes | Yes | Yes |
| Katamanda | No | Yes | Yes | Yes |
| Magodi | No | No | No | No |
| Sinda | No | No | No | No |

Chibwika and Katamanda may be technically sustainable now but may become unsustainable if tariff structures are not sustainably aligned. Magodi and Sinda SMG were found unsustainable in any dimension and this is because Sinda SMG is currently not operating at full capacity while Magodi is not operational at all.

CHAPTER 6

6.0 CONCLUSION, COMMON CHALLENGES AND RECOMMENDATIONS

6.1 Conclusion

This study examined five major solar mini-grids in Zambia from four sustainability perspectives, viz. technical, economic, social and environmental. The study updated information and documentation on five (5) SMGs studied. The study found that the sustainability of a project is not solely dependent on its technical viability but also on economic, social, and environmental sustainability.

Technically Magodi and Sinda solar plants were found to be not viable due to lack maintenance. The system configuration for Magodi SMG as of its first inspection did not have sufficient voltage to charge the batteries and hence was completely overhauled. However, the system overhaul did not work because the poor system configuration had already damaged the batteries (some batteries bulged and lost battery capacity). Furthermore, the system was not protected from lightning and had no circuit breakers, resulting in frequent lightning strikes and damaged the inverters and charge controllers. As the plant was highly unsustainable financially, it couldn't meet its OPEX, repairs and replacements costs. Moreover, there was no technical training offered to the local operators left to run the plant. However, the SMG was oversized by 14 kW during its operation days.

Sinda SMG is currently neither undersized nor oversized. The system is protected from lightning via the use of surge arrestors. However, the initial battery bank consisted of forty-eight (48) 2 V batteries got damaged within a year of operation leading to frequent downtimes. Data revealed that the batteries were not labelled (no specifications) giving suspicions that they were below the required standards. Despite the new set of twenty-four (24) 6V, 556 Ah batteries that were installed, the plant still did not supply power 24/7. This could be due to lack of technical experts at the site to maintain and operate the SMG.

At the time of the study, Chibwika, Chitandika, and Katamanda were still technically sustainable. All the three (3) SMGs were protected from lightning and were able to provide power 24/7 despite few technical challenges due to system configuration. Chibwika SMG was undersized by 5.4 kW. The solar plant was failover system with a diesel generator to ensure 24/7 power supply. The system

overloads at times due to the system circuit breaker rated at 16 A which is capable of operating a pressing iron and other elements. For now, the SMG may be technically sustainable but can only hold up for few more years as the financial unsustainability of the plant takes its toll. Chitandika SMG was highly undersized by 58 kW. The reason for this was that power producer (Engie power) having realized the high commercial energy demand in the community, allowed more connections to machinery (hammer mills, grinders, etc.) to the plant without considering the SMG maximum energy generation capacity. This posed a high risk to technical sustainability of the plant. Katamanda SMG is oversized by 11 kW. However, the low fixed tariff mode of payment led to careless use of solar power which is likely going to cause system overload in the near future making the plant technically unsustainable. The inverters and charge controllers of the system are embedded in one control system and have no technical specifications. PV modules are wrongly inclined at 36°. Furthermore, the plant has no qualified technicians to maintain it leaving the headman of the village to operate the SMG.

The study found the five (5) SMGs were financially unsustainable due to their high upfront capital costs (CAPEX). The plants would not recover the CAPEX within the lifespan of the solar components. However, by implementing an estimated tariff structure ranging from USD 0.40/kWh to USD 0.57/kWh would make the plants financially sustainable. Chibwika, Katamanda, and Magodi used very low fixed tariff structures of USD 3.13(ZMW 50)/month, USD 0.75(ZMW 12)/month, and USD 1.88/month respectively. These tariffs are not viable for financial sustainability. The calculated viable tariff structures for maintenance and OPEX are USD 0.57/kWh, USD 0.40/kWh, and USD 0.50/kWh for Chibwika, Katamanda, and Magodi respectively. Chitandika and Sinda SMGs used pay as you go tariff structures of about USD 0.38(ZMW 6.08)/kWh and USD 0.31(ZMW 5)/day respectively. The sustainable tariff structure for Chitandika is USD 0.43/kWh and that of Sinda is USD 0.56/kWh. These sustainable tariff structures calculated are too high compared to Zambian Electricity Supply Corporation (ZESCO)'s residential tariff for consumption of about 300 units at USD 0.07(ZMW 1.15) /kWh. This is due to two main reasons. First, utility tariffs generally have significant subsidies. Secondly, solar mini-grids operate at a much smaller level resulting in their overhead costs being relatively high. The study further revealed that the low income and low capacity to pay in rural areas do not in general allow charging of full economic tariffs from the rural households. So solar mini grids in rural areas are generally not fully sustainable. The study found that providing a minimum subsidy in a smart way could help sustain the business in the best case scenario

The study further revealed that the SMGs are socially and environmentally sustainable. The availability of entertainment such as watching soccer via TVs has brought the community together and has connected them to the outside world. Environmentally, the use of solar power has proven to have a great impact on the communities. Table 53 shows the reduction in the number of households using kerosene and candles for lighting after the implementation of the SMGs leading to a reduction in GHGs emissions. For detailed explanation refer to sections 5.1 and 5.2.

In general, the findings reveal that the sustainability of solar mini-grid projects is multidimensional and a project could fail if any dimension or a combination is unsustainable. In other words, the failure of a project may not necessarily mean it is not technically feasible as the failure may be due to poor implementation of its economic, social, and environmental dimensions. The study revealed that solar mini-grid electricity has proven to be a reliable source of energy in the rural areas which are far from the national or main-grid. It is a perfect way of promoting developmental activities and creating opportunities for the rural area dwellers.

6.2 Common challenges

Drawing lessons from this study, it can be deduced that successful implementation and good performance at the early stage of the lifecycle of a solar mini-grid is not an appropriate indicator of its success. Therefore, for a project to be sustainable, all four dimensions (economical, technical, social, and environmental) must be correctly planned and implemented. This is necessary as it was noted that, though, many of these problems only occur later in the project's lifecycle, their causes are prior to the planning of the project. Some of the common challenges of SMGs in Zambia;

1. Lack of good feasibility studies: - This has resulted in solar mini-grid developers oversizing or under sizing the SMGs due to lack of knowledge on the load conditions and economic activities of the area. The oversized mini-grid resulted in higher initial investment and increased operational costs leading to financial and technical unsustainability. On the other hand, undersized solar mini-grids tend to be overloaded, leading to technical unsustainability.
2. Lack of standards for components of solar PV systems used in these solar mini-grids: - Inadequate standards for components of solar PV systems used in these solar mini-grids have

been observed with some visited SMGs lacking proper labelling specifications for critical components such as inverters, charge controllers and batteries.

3. Lack of technical training to people left to run the solar mini-grids after implementation: - Projects could also fail due to lack of trained personnel to oversee the daily operations and routine maintenance of projects. This is evident from Sinda SMG where the system was initially using 48 2V batteries which within a year of operation half of the batteries were damaged leading to the plant's failure to supply power 24/7. The suppliers and the company blamed each other, with suppliers citing some substantial ignorance from the side of the technicians on how to best ascertain continued operation of the batteries.
4. Poor handing over of projects funded by donors lead to poor monitoring of the systems: The people left to run the plants lacked knowledge of operating the system technically and business wise. This is evident in three (3) community owned (Chibwika, Katamanda and Magodi) solar mini-grids which have very low fixed tariff structures to sustain OPEX and maintenance of the plants.
5. Lack of internet network facilities in rural communities is a major factor preventing the integration of remote monitoring facilities of solar mini-grid projects in Zambia: - This often makes most maintenance activities difficult in case of emergency. The project becomes non-functional for long periods while project managers mobilize for corrective maintenance.
6. The solar mini-grid owners do not stick to the original plans on the plant capacity load: - Most of the plants are taken as pilot studies, so when the owners discover high connection opportunities, they tend to connect more loads than the plant capacity resulting in the plant being undersized leading to technical unsustainability.
7. Lack of labelling solar components in English (official language): - This is evident in SMGs constructed by the Chinese (Chibwika and Katamanda) where all the components are labelled in Chinese. The best case scenario is when the uninterrupted power supply (UPS) at Katamanda SMG developed a faulty, the local operator failed to fix the UPS problem as it was labeled in Chinese language and he could not read and understand the language. The problem was only fixed by the same Chinese constructor who only came after about a month of no power supply.
8. High levels of projects abandoned by the project owners: - The researcher suspects that the project owners overprice the projects, resulting in high upfront cost to set the solar mini-grid

and receive large funding from the donors. Due to this overpricing, project owners recover their full investments upfront before construction of the SMG, and are no longer interested in connecting the agreed number of households and/or continued operation of the solar mini grid.

6.3 Recommendations

Based on the challenges stated above, the following recommendations are provided to ensure the sustainability of solar mini-grid projects in Zambia;

1. Before implementation of any solar mini-grid in the country, the government of the Republic of Zambia and energy agencies should make it a requirement to do feasibility studies on project sites in order to assess the energy demand and economic activities of the area.
2. The National Standards body, Zambia Bureau of Standards (ZABS), should work with Ministry of Energy (MoE), Energy Regulation Board (ERB), Rural Electrification Authority (REA) and other stakeholders in renewable energy industry to adopt standards for components of solar PV systems to be accepted for importation into the country. Such standards should focus on the level of products' quality as well as their adaptability to the prevailing climatic conditions in the various parts of the country.
3. There is need for the development of a national curriculum for compulsory training and certification programme for installers and technical operators of solar mini-grids. This will ensure that technical operators responsible for running the plants at the site have the necessary. The curriculum should cover topics such as safety, design, installation, maintenance and troubleshooting of solar PV systems. Establish a mandatory registration process for organisations involved in solar PV installations. This will help track poorly implemented projects and identify charlatans in the industry.
4. There should be a lot of sensitization and training on the O & M costs of solar mini-grids before the donors announce the plants as donations to the community. This will help the community to fully understand their responsibilities for the operation and maintenance of the systems. The community should be made aware that neglecting the operation and maintenance costs of solar mini-grids could lead the system failing, which could result in financial losses. Before handing over of the project to the community, develop a clear plan and outlined guide

for income generation that will enable the community to raise funds for the operation and maintenance of the SMGs.

5. There is need for strategic planning towards the development of rural communities in Zambia. The government should work together with internet providers such as Zamtel, Airtel and MTN in building network towers for rural areas because the availability of internet service in such areas is essential to facilitate remote monitoring of solar PV mini-grid projects.
6. Create a system of monitoring and evaluating the performance of solar mini-grids installed across the country. This will help identify any technical issues or inefficiencies and ensures that the systems are operating at their full capacity. The data collected from the monitoring system can be used to inform future improvements in the design and operation of solar mini-grids. Clear communication regarding the capacity and scope of solar energy projects is essential for managing expectations and prevent disappointment among consumers. The consumers will be able to make informed decisions regarding their energy needs and plan/budget accordingly knowing what appliances can be powered by the solar plant and what energy sources they may need to rely on for high voltage appliances.
7. There is need for translating the literature from Chinese language to English and local languages for easy reading and understanding of the system manual operation books.
8. The government of the republic of Zambia in conjunction with other energy stakeholders should come up with stiff punishments to solar companies that abandon their projects due to the fact that they already made money via exaggerated upfront cost from the donors. There should be clear monitoring of these solar mini-grids in the country. This monitoring will make plant owners stick to their initial plans and supply power to the communities as planned from the beginning.

6.4 Recommendation for further studies

Undertake a detailed study of the technical configuration and operation of the oversized and undersize solar mini-grids in order to ensure efficient operation of the plants. The data collected and analyzed will be used to improve future design and operation of solar mini-grids. This will result in SMGs being technically sustainable and improve the other three (financial, social, and environmental) dimensions of sustainability.

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APPENDICES

Appendix 1

Questionnaire for connected & non-connected households of the communities.

Geographical location.....

1. Gender

| | |
|------|--------|
| Male | Female |
| 1 | 2 |

2. Age (Years)

| | | | | |
|---------|---------|---------|---------|----------|
| 20 – 30 | 31 - 40 | 41 - 50 | 51 - 60 | Above 60 |
| 1 | 2 | 3 | 4 | 5 |

3. What is the highest level of education you have attained?

| | | | |
|---------|-----------|---------|------------|
| Primary | Secondary | College | University |
| 1 | 2 | 3 | 4 |

4. Family size

| | | | | | |
|---|---|---|---|---|----|
| 1 | 2 | 3 | 4 | 5 | >5 |
| 1 | 2 | 3 | 4 | 5 | 6 |

5. Number of school children

| | | | | | |
|---|--|---|---|---|----|
| 1 | | 2 | 3 | 4 | >5 |
| 1 | | 2 | 3 | 4 | 5 |

6. How has the access to electricity benefited the school children?

| | |
|----------------------|----------------------|
| Extended study hours | Improved performance |
| 1 | 2 |

Other.....

7. Size of house (number of rooms)

| | | | | |
|---|---|---|---|----|
| 1 | 2 | 3 | 4 | >5 |
| 1 | 2 | 3 | 4 | 5 |

8. Condition of housing

| | | |
|----------------------|--------------|--------------------|
| Mud & grass thatched | Mud & roofed | Concreted & roofed |
| 1 | 2 | 3 |

9. Occupation

| | | | |
|--------|-----------|-------------|---------------|
| Farmer | Fisherman | Businessman | Civil Servant |
| 1 | 2 | 3 | 4 |

Other:

10. Average monthly income in Zambian kwacha

| | | | | | |
|-----------|-----------|----------|-----------|----------|-----------|
| Below 100 | 100 – 300 | 301- 500 | 501 - 700 | 701- 900 | Above 900 |
| 1 | 2 | 3 | 4 | 5 | 6 |

11. Total household income

| | | | | | |
|-----------|-----------|----------|-----------|----------|-----------|
| Below 100 | 100 – 300 | 301- 500 | 501 - 700 | 701- 900 | Above 900 |
| 1 | 2 | 3 | 4 | 5 | 6 |

12. What are the types of income your family get?

| | | |
|--------|--------------------|----------|
| Salary | Retirement pension | Business |
| 1 | 2 | 4 |

Other.....

13. How is the income spread?

| | | | |
|-------|--------|---------|----------|
| Daily | Weekly | Monthly | Annually |
| 1 | 2 | 3 | 4 |

14. What are the Peak income months?

.....

15. What kind of expenditure are most typical for your family?

| | | | |
|------|---------|-------------|--------|
| Food | Grocery | School fees | Energy |
| 1 | 2 | 3 | 4 |

Other.....

16. How much do you spend per month on each of the items selected in question 15?

Food.....Grocery..... School fess..... Energy.....
 Other.....

17. Are you connected to the Solar Mini-grid?

| | |
|-----|----|
| Yes | No |
| 1 | 2 |

If Yes, when were you connected?

Month Year.....

If No, state the reason:

| | | |
|---------------|----------------------|-----------------|
| Cannot afford | Service is expensive | Service is poor |
| 1 | 2 | 3 |

Other:

18. What electric appliances do you own?

| | | | | |
|------------------|------------------|------------------|------------------|------------------|
| B/W TV | Color TV | Radio | Fridge | Computer |
| Power rating (W) | Power rating (W) | Power rating (W) | Power rating (W) | Power rating (W) |

Other:.....

19. What appliances did you own before the implementation of the solar mini – grid?

| | | | | |
|------------------|------------------|------------------|------------------|------------------|
| B/W TV | Color TV | Radio | Fridge | Computer |
| Power rating (W) | Power rating (W) | Power rating (W) | Power rating (W) | Power rating (W) |

Other:.....

20. What sources of energy did you use to power the appliances in question 19?

| | | | |
|-------------|-----------|--------------|-----------|
| Car battery | Generator | Battery lamp | Own solar |
| 1 | 2 | 3 | 4 |

Other:.....

21. How much monthly did you spend on using the appliances in question 19?

| | | | | |
|----------|---------|----------|-----------|-----------|
| Below 50 | 50 -100 | 101 -150 | 151 - 200 | Above 200 |
| 1 | 2 | 3 | 4 | 5 |

22. How much monthly do you spend on using the appliances in question 18?

| | | | | |
|----------|---------|----------|-----------|-----------|
| Below 50 | 50 -100 | 101 -150 | 151 - 200 | Above 200 |
| 1 | 2 | 3 | 4 | 5 |

23. Sources of energy used for lighting before implementation of the solar mini – grid?

| | | | |
|--------|----------|--------------|-----------|
| Candle | Kerosene | Battery lamp | Own solar |
| 1 | 2 | 3 | 4 |

24. What do you use for lighting?

| | | | | |
|--------|----------|--------------|-----------|-----------|
| Candle | Kerosene | Battery lamp | Own solar | Mini-grid |
| 1 | 2 | 3 | 4 | 5 |

25. What is the intended purpose of lighting?

| | | | |
|----------|----------------|----------------|-----------------|
| Security | House lighting | Pupil studying | Office lighting |
| 1 | 2 | 3 | 4 |

26. Number of bulbs in use: Power rating of each bulb (W).....

| | | | | |
|---|---|---|---|----|
| 1 | 2 | 3 | 4 | >5 |
| 1 | 2 | 3 | 4 | 5 |

27. How much do you spend on lighting per month in kwacha?

| | | | | | |
|---------|---------|---------|---------|---------|----------|
| 10 - 20 | 21 - 30 | 31 – 40 | 41 - 50 | 51 - 60 | Above 61 |
| 1 | 2 | 3 | 4 | 5 | 6 |

28. What source of energy do you use for cooking and heating?

| | | | |
|----------|-----------|-----|----------|
| Charcoal | Generator | Gas | Firewood |
| 1 | 2 | 3 | 4 |

Other:.....

29. How much do you spend on cooking/heating every month in kwacha?

| | | | | |
|----------|---------|----------|-----------|-----------|
| Below 50 | 50 -100 | 101 -150 | 151 - 200 | Above 200 |
| 1 | 2 | 3 | 4 | 5 |

Other.....

30. How much do you spend per month on powering a TV set, Radio and Charging cell phones?

| | | | | |
|----------|---------|----------|-----------|-----------|
| Below 50 | 50 -100 | 101 -150 | 151 - 200 | Above 200 |
| 1 | 2 | 3 | 4 | 5 |

31. How much are you willing to pay for electricity per month in kwacha? (check total household income).

| | | | | | | | | | | |
|----|----|----|----|----|----|----|-----|-----|-----|-----|
| 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 | 130 | 150 | 200 |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |

32. How much do you pay for electricity per month in kwacha?

| | | | | | | | | | | |
|----|----|----|----|----|----|----|-----|-----|-----|-----|
| 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 | 130 | 150 | 200 |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |

33. What is the mode of payment for electricity?

| | |
|-------------------------------|---|
| Use mobile money/bank account | Travel to the mean grid to purchase units |
| 1 | 2 |

34. Do you have a prepaid meter?

| | |
|-----|----|
| Yes | No |
| 1 | 2 |

35. Would you like a prepaid meter or fixed charge?

| | |
|--------------|---------------|
| Fixed charge | Prepaid meter |
| 1 | 2 |

Give a reason for your preference.....

36. Do you have power 24/7?

| | |
|-----|----|
| Yes | No |
| 1 | 2 |

37. If your answer is no to question 36 give a reason why?

.....

38. How satisfied/dissatisfied are with the service offered by the management?

| | | | |
|-----------|----------------|--------------|-------------------|
| Satisfied | Very satisfied | Dissatisfied | Very dissatisfied |
| 1 | 2 | 3 | 4 |

Give a reason for your answer.....

39. Would you be willing to pay more if management supplied more electricity?

| | |
|-----|----|
| Yes | No |
| 1 | 2 |

40. If the answer to question no. 39 is Yes, what would you do with the increased electricity supply?

.....
.....

41. How quickly does management attend to problems related electricity supply?

| | | | |
|---------|--------------|--------|-------------|
| Quickly | Very quickly | Slowly | Very slowly |
| 1 | 2 | 3 | 4 |

42. What other benefits have accrued to the community arising from the provision of electricity services?

Entertainment

Reduced crime prevalence

Extended business hours

Improve health delivery

Improved education delivery

Other.....

Sign:

Date:

Appendix 2

Questionnaire on project design, financing, construction, management & operation

- i. Name and contact of the company which constructed the Mini-grid.
- ii. Which month and year was the mini grid set up?
- iii. Who financed the Project?
- iv. What was the total cost of the mini grid?
- v. What was the financing mechanism? (Loan, grant, subsidy etc.)
- vi. Who designed the Mini-grid?
- vii. What was the motivation for setting up the Mini-grid?
- viii. Is the mini-grid private or government owned?
- ix. Who conducted the feasibility studies?
- x. How long did it take to commission the project from time the feasibility studies were undertaken?
- xi. What were the major challenges faced during construction?
- xii. Are electrical engineering documents consisting of site plans, architectural plans, locations and equipment layout diagrams of all electrical and power distribution rooms and enclosures available?
- xiii. What were the some of the challenges faced during the implementation of Project? (land acquisition, road network, financing, local regulation, shipment etc).
- xiv. Initial number of households connected to the Mini-grid
- xv. Current number of households connected to the grid
- xvi. Has the number increased or decreased? Account for the difference
- xvii. How many schools, clinics and churches are connected to the Mini-grid?
- xviii. How many businesses are connected to the Mini-grid?
- xix. Do customers default on payments? If Yes, what is annual default rate?
- xx. How far is the main utility grid and at what voltage is it transmitted?
- xxi. How long did it take to commission the project from the time the feasibility studies were undertaken?
- xxii. Who are the current Project/Mini-grid managers? Designations?
- xxiii. What technical/financial/business training was offered to the Project/Mini-grid managers?

- xxiv. Was the basic technical training related power generation, transmission, usage, limitation of solar power and safety offered to the customers?
- xxv. How was the training delivered? Was the documentation translated into local languages?
- xxvi. How much power is consumed by businesses, and how much by households, schools, churches and clinics? (rough estimation if precise data not available)?
- xxvii. What is the monthly revenue of the system?
- xxviii. What is the monthly energy charge? Can you specify the tariff structure?
- xxix. Does the system meet the energy demands of the customers?
- xxx. What are the annual expenses (OPEX) for the system?
- xxxi. What are the monthly expenses on salaries and operations?

Sign:

Designation:

Date:

Appendix 3

Questionnaire on technical configuration of solar mini-grid.

2.3.1 PV Modules

- i. Peak Power of the system (W_p)
- ii. Site Peak Sun Hours (Hours)
- iii. Manufacturer
- iv. Model Dimensions (l x w x h) Weight (kg)
- v. PV module orientation & inclination
- vi. PV module type (Mono, Poly, Thin film)
- vii. PV modules tested in accordance with IEC 61512 specifications?
- viii. Number of PV modules
- ix. Numbers of PV modules in one string
- x. Number of PV modules in parallel

- viii. What preventive maintenance do you perform on the controller and how often?
- ix. What is the warranty period for the controller?

2.3.5 System & Distribution Wiring

- i. Wire size between PV module and combiner box (mm²)
- ii. Wire size between combiner box and Charge controller (mm²)
- iii. Are the combiner boxes fused? If Yes, what is the amperage (A) rating of the fusing?
- iv. Estimated voltage loss between the PV modules and the Powerhouse?
- v. Distribution wire size (mm²)
- vi. Voltage loss between the Powerhouse and the furthest connection
- vii. Is the distribution network protected from lightning? If Yes, what protection is employed?

2.3.6 General

- i. Area (m²) under which the solar mini-grid is built.
- ii. What is the average Daily Energy Production (kWh)?
- iii. What is the average Daily Energy Consumption (kWh)?
- iv. How is the energy production and consumption monitored? Does the system employ data logging facilities?
- v. Have there been any technical modifications since the original installation (if yes which?)
- vi. If Yes, how has the modification affected the power generation?
- vii. What is the average distance from a connected customer to the power source?
- viii. Does the system provide energy 24/7? Please specify supply profiles for a 24-hour day averaged over the last full month?
- ix. Are there currently power restrictions? Upper limit for power or limited hours?

SIGN.....

DESIGNATION.....

DATE.....

Appendix 4

questionnaire for socio-economic variables.

- i. What is the community's perception of solar power?
- ii. What are the levels of satisfaction?
- iii. What are the major economic activities in the project area?
- iv. Are the activities seasonal?
- v. What are the peak income months?
- vi. Has the provision of electricity service catalysed economic activities in the Project area?
- vii. What are some of the positive and negative social impacts?
- viii. How has the provision of electricity benefited the education and health sectors?
- ix. What are some of the productive uses of electricity in the community? (food processing, welding, water pumping, sewing, ice making etc).
- x. Are there currently incentives for users in this tier?
- xi. What are main barriers to productive use of electricity and how can they be mitigated?
- xii. What energy capacities (kWh per day) can the mini-grid sustain?
- xiii. Is it feasible to shift productive uses to off-peak times?
- xiv. During which period of the day is electricity consumption at peak?
- xv. Is the population expected to grow or decrease in the next 5 years?

Sign:

Designation:

Date: