EXTENDING ENERGY USAGE OF SOLAR MILLING PLANTS INITIATIVE IN THE EASTERN PROVINCE OF ZAMBIA

BY

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A dissertation submitted in partial fulfilment of the requirements for the degree of Master of Science

The University of Zambia

DECLARATION

I, **KAYOMBO KASONGO LEVY**, declare that this dissertation represents my work and has not been submitted at this or any other University for the award of a degree. Furthermore, this dissertation does not incorporate published work or materials from another dissertation.

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APPROVAL

This dissertation of **Kayombo Kasongo levy** has been approved as partial fulfilment of the requirements for the award of the Degree of the Master of Science in Physics by the University of Zambia.

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ABSTRACT

Zambia's National access to electricity is approximately 31 %, with 67 % of the urban having access and worse off in rural areas, which are very remote and far away from the electricity grid, with only 4 % of its population having access. Rural areas do not just need electricity for everyday uses like lights and heat but also for productive uses such as farming and clean water provision.

The purpose of this study was to conduct a survey to assess the technical configuration and performance of the solar hammer mills (SHMs), assess the average daily energy generated, energy consumed and excess unutilised energy of selected solar milling plants (SMPs), conduct energy needs assessments for the surrounding rural communities and finally to design an effective technical solution to ensure productive use of the excess solar energy from the respective SHMs.

Visits to six selected solar milling plants in Eastern Province were undertaken. The average daily energy generated, energy consumed, and excess unutilised energy were investigated and recorded. A household and technical questionnaire was designed and administered to evaluate the community's energy needs. Excel and a statistical package for social sciences (SPSS) were used to analyse and interpret the collected data. Finally, a concept design for a solar water pumping system and a business hub around the SMP was recommended to benefit the local communities.

It was found that the second and third generations of SHMs were lower power-rated and were technically friendly to the local operators. From the household survey, the average number of houses within a 500 m radius ranges from 25 to 30, with an average number of rooms ranging from five to eight. Furthermore, the community's economic activities were found to be farming and business, with an average annual income going from ZMW16,000.00 to ZMW20,000.00. Moreover, an average of 67 % of the people use firewood for cooking, while 74 % of the people, on average, use solar lamps for lighting. Lastly, a 15 kW hybrid inverter was recommended to connect a solar water pump and a business hub around the SMP. This class of inverter can handle high voltages from the SMP solar array. A 1.5 kW solar water pump was selected to manage the total water demand of 30,000 L/day. Regarding business, a minimum of 7.6 kW is required to meet the demand for shops and security lighting. A 5,900 Ah battery bank is required to supply power to the system to meet power downtimes.

DEDICATION

To my beloved wife, Lucina Chendela Kayombo and my parents, Mr. Levy Kayombo Mununga and Mrs. Cellar Mwale Kayombo.

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ACRONYMS

AC Alternating Current

BOS Balance of Systems

CO_2 Carbon dioxide

COD Commercial Operation Date

COVID-19 Corona Virus Disease of 2019

DC Direct Current

DED Daily Energy Demand

DoD Depth of Discharge

EBM Energy Balance Method

ENS Energy Needs Assessment

EPA United States Environmental Protection Agency

HRES Hybrid Renewable Energy System

ISP International Science Programme

IPCC Intergovernmental Panel on Climate

LCC Life Cycle Cost

MOE Ministry of Energy

MOU Memorandum of Understanding

MPPT Maximum Power Point Tracking

MSMEs Micro, Small and Medium-Sized Enterprises

PPA Power Purchase Agreement

PUE	Productive Use of Energy
PV	Photovoltaic
RE	Renewable Energy
REA	Rural Electrification Authority
SDGs	Sustainable Development Goals
8NDP	Eighth National Development Plan
SEC	Solar Energy Centre
SHMs	Solar Hammer Mills
SMPs	Solar Milling Plants
SPSS	Statistical Package for Social Sciences
SSA	Sub-Saharan Africa
SWP	Solar Water Pump
UNZA	University of Zambia
USAID	United States Agency for International Development
WEF	Water-Energy-Food
ZCF	Zambia Cooperative Federation

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CHAPTER 1: INTRODUCTION

In this chapter, the outline of the background to this study, the statement of the problem, the purpose of the study, research objectives, research questions, significance of the study and organisation of the report are given.

1.1 Background

Globally, around 4 billion people have no access to electricity or modern cooking technologies. Moreover, this harms the affected population's quality of life, environment, health, education, and income [1]. The challenges faced in Sub-Saharan Africa (SSA) are; a lack of access to essential resources such as water, energy and food. Expected demand growth by 2030 and the climate change impact also stress the already limited resource supply systems and infrastructure [2]. To put this into perspective, approximately 600 million people in SSA will still lack access to electricity due to a 70 % perceived electricity demand growth by 2030 compared to 2016 [3].

Furthermore, about 374 million people experience severe food insecurity. Compared to the 2015 levels, the food demand will grow by 60 % in 2030. Regarding water, approximately 737 million people lack access to safely managed drinking water. Additionally, water consumption is expected to increase by 283 % in 2030 compared to 2015 [4].
In the Zambian context, 3,307.43 MW is the installed electricity generation capacity, with 85 % being hydro-based and the remaining 25 % from other energy sources. National access to electricity is around 31 % of the Zambian population, with 67 % of the urban and worse off in rural areas, with only 4 % of its population having access to electric power [5]. This shows that access to energy services remains a big challenge for the rural populations in Zambia. Most people in rural areas are not electrified and heavily depend on unsustainable non-renewable energy resources [6]. Rural areas do not just need electricity for everyday uses like lights and heat but also for productive uses such as farming and clean water provision [7].

To tackle the challenge of limited energy access in rural areas, the Government of the Republic of Zambia through the Zambia Cooperative Federation (ZCF) recently embarked on a Solar Milling Plant (SMP) initiative to mitigate the high cost of mealie meals in rural areas. Furthermore, ZCF signed a Memorandum of Understanding (MoU) with the Rural Electrification Authority (REA) to ensure proper utilisation of excess solar energy from the

SMPs. ZCF has installed 1,580 SMPs across Zambia, and the installed SMPs are in three different generations with different installed capacities. The first-generation machines utilise about 7.5 kW out of the 15 kW installed, while the second and third-generation machines utilise 3.8 kW out of the 12.5 kW installed, leaving approximately 12 MW of excess power across the country unutilised. Therefore, properly using this excess energy may also help most economically unsustainable projects. REA is facing the challenge of how this excess power could be put to productive use by the surrounding communities [6].

Nationally, this work will contribute to Zambia's Eighth National Development Plan, increasing renewable energy sources, in the national installed electricity capacity, excluding large hydroelectricity generation to about 10 % from 3 % as of 2021[8]. Therefore, to increase supply, there is a need for additional investment in other sources of energy, such as solar energy generation. This increased investment in the sector will result in an increase in electricity generation capacity to 4,457 megawatts (MW) by 2026 [8]. This is also in line with achieving the seventh Sustainable Development goal of the United Nations which states that by 2030, we should ensure universal access to affordable, reliable and modern energy services [9].

1.2 Statement of the problem

There are 1,580 SMPs in Zambia installed by ZCF. Little or no research has been done to assess their performance and possible extension of the excess power produced to channel it for productive use.

In addition, there remains a gap in how to make the SMP’s project sustainable in socio-economic and techno-economic terms. On the other hand, this is explained by the mismatch between community needs and the design of energy projects. These projects are not designed to ensure a connection between access to energy and other development objectives [10]. Currently, these SMPs are solely performing the milling job and are not addressing other essential community needs. Consequently, this research takes advantage of this shortcoming and proposes a sustainable solution to promote the productive use of energy (PUE). The foremost idea is that the water, energy and food sectors are interconnected and the security of one of them depends on the other two [11]. If SMPs are integrated with investments along the food value chain and other productive uses of energy, they can bring substantial development outcomes and subsequently entice the attention of governments, international development agencies, and investors [12].

1.3 Aim

This research aims to study the performance and possible extension of excess energy from SMPs to productive uses in surrounding rural communities of Eastern Province.

1.4 Objectives

i) To assess the technical configuration and performance of the three generations of the SHMs.

ii) To assess the average daily energy generated, energy consumed and excess unutilized energy of selected SMPs.

iii) To conduct energy needs assessments for the surrounding rural communities.

iv) To recommend a design of an effective technical solution to ensure the productive use of excess solar energy from SMPs.

1.5 **Research questions**

i) What is the main difference, and which one is the best performing among the three SHMs generations?

ii) How much average energy per day is produced, consumed and unutilized?

iii) What are the needs of the surrounding communities?

iv) What effective technical solution design should be recommended to ensure the productive use of excess solar energy from SMPs?

1.6 Significance of the study

The knowledge of this study will directly benefit the members of rural communities. Members of the community will have access to energy services such as battery charging, clean water, photocopying, saloons, internet, etc. Moreover, it will be helpful to various institutions such as the Zambia Cooperative Federation (ZCF) and the Rural Electrification Authority (REA). These institutions will make informed decisions regarding the use of excess energy. Therefore, this research will help policymakers in Zambia through the Ministry of Energy to plan energy investments effectively and further contribute to the knowledge of PUE.

1.7 Organization of the report

This report is structured into five chapters. Chapter 1 highlights the background of the report, and Chapter 2 provides reviews of the literature on similar studies. Chapter 3 outlines the research methodology used in this study, Chapter 4 presents the results and discussion of the findings, and Chapter 5 presents the study's conclusion and recommendations based on this study's findings.

CHAPTER 2: LITERATURE REVIEW

2.1 Background and local context

Developing a sustainable, long-term solution to meet global energy needs is challenging [13]. Energy is directly related to the world's significant global challenges, such as poverty reduction, climate change, the global environment and food security. Existing energy systems cannot respond to the needs of the world's underprivileged. Around the world, 2.6 billion people rely on traditional biomass for cooking, and 1.6 billion people (about a quarter of the human race) do not have access to electricity. The projected cumulative investment required between 2005 and 2030 to meet energy needs is almost US$20.1 trillion [13]**.** However, even if this investment is made over the next thirty years, 1.4 billion people will still lack access to electricity in 2030, and 2.7 billion will still rely on traditional biomass for cooking and heating [14].

Global energy-related carbon dioxide (CO_2) emissions are expected to increase by about 50 % between 2004 and 2030 unless significant policy reforms and technologies are introduced to transform how energy is produced and consumed [12]. Coal has surpassed oil as the primary contributor to global CO_2 emissions [13]. Developing countries will account for three-quarters of the increase in carbon dioxide emissions between 2004 and 2030 unless significant transformative policies and technologies are introduced in the years ahead. Per capita emissions in developing countries may continue to be low relative to those in developed countries [10].

Nevertheless, the share of developing country emissions is expected to rise from 39 % in 2004 to over half of the total world emissions in 2030 unless mitigated by policies that promote more efficient production and use of energy, switching to cleaner fuels, more efficient transportation, and cleaner electricity supply. Many rapidly growing developing countries must make significant energy investments over the next decade. There is little time to ensure that energy infrastructure and industrial facilities are energy efficient [14].

In the Zambian context, reports say that more than 93 % of Zambia's rural population does not have reliable access to water and electricity [16]. Climate change-related drought between 2013 and 2020 exacerbated the situation and threatened the country's water and food supply [16]. In addition, threats to food security have been compounded by the COVID-19 pandemic, which has devastated communities and crippled local small businesses. Small-scale farmers have been adversely affected by the restrictions on public gatherings and the need to comply with all other health guidelines. Ultimately, this has affected their household income [17].

Furthermore, more than 2.3 million people have been and remain affected, and at least 430,000 people suffer from severe food insecurity, described as below starvation. With this disaster, the resilience of local farmers was compromised, particularly for women and young people and their households, which led to most homes depending on wild fruits and, in some cases, relief food. The COVID-19 pandemic has disrupted humanitarian efforts to provide needed support as attention has shifted to preventing the spread of the pandemic. It is also worth noting that with the arrival of COVID-19, the burden of unpaid care work will upsurge for women and girls, with children who can no longer go to school and have to spend time at home and, worse still, in instances where family members are affected by the virus. Usually, women refocus their attention on providing care for the sick [17]. Time spent on care could have been spent on agricultural activities such as food production or the sale of agricultural produce [14].

2.2 Solar milling plants in Zambia

Solar milling plants in Zambia are a recent development in the country's agriculture sector. Research indicates that the introduction of the Solar Milling Plants (SMPs) was part of the broader Presidential Milling Plant Initiative, which came into being following the Zambian 6th President, Edgar Chagwa Lungu's visit to China in March 2015. This initiative centred on the acquisition of solar-powered milling facilities, funded through a loan obtained from the China Development Bank. Concerning ownership and administration, it clarifies that the Zambia Cooperative Federation (ZCF) assumed responsibility for the management of these solar milling plants, which were subsequently entrusted to cooperatives for accessibility. The cooperatives were entrusted with the operation and oversight of these mills, making them available for individuals to utilize for grinding their agricultural produce. The main objectives of this project encompassed various aspects such as the creation of job opportunities, the production of affordable mealie-meal, and the sale of bran as a by-product [18].

The benefits of Zambia's SMPs were also shown in several other studies. For example, a study conducted in the Eastern Province of Zambia has shown that there have been increases in maize production as well as improvements in flour quality and decreases in harvest losses following the installation of solar milling facilities [19]. In addition, another study has shown that the time and labour required for maize processing are reduced by solar maize processing plants, resulting in increased productivity and income for farmers, as well as increased productivity and income for farmers [20].

The operation and performance of SMPs have been reported in the other studies carried out by REA [6]. There are 1580 installed SMPs, and they are distributed throughout the 10 provinces of Zambia as follows: - Eastern Province (307), Southern Province (266), Central Province (256), Northern Province (183), Muchinga (138), Copperbelt (133), North-Western (106), Luapula (98), Lusaka (65) and Western province (28). Out of the total SMPs, 676 SMPs are the first generation, while the rest are the second and third generation. The performance and operation of SMPs were measured using the following parameters; the monthly revenue, monthly costs, ability to re-pay the loans and involvement of the cooperative [6].

There were two types of tariffs charged for milling services by SMPs cooperatives. The first one was tolling milling, where individuals would bring small quantities of their grain for home consumption. The other type of milling involved a situation where the cooperative would buy grain in bulk, process the mealie meal, package and sell it to customers on a retail or wholesale basis. However, the tolling tariff was the most common tariff charged by all the SMPs. Charging for milling services is not done uniformly across the SMPs as cooperatives use different measuring units, others use empty buckets of various sizes, and others charge per kg. However, on average, it was established that 1 kg of maize grain (the most milled grain) costs about ZMW0.33. REA also reported that 82 % of the cooperatives could not pay the loans as stipulated in the contract, and only 18 % were managing. The data also showed that 73 % of the cooperatives are involved in extra-income fundraising ventures, while 27 % are not [6].

The data collection revealed that the current state of the SMPs would allow for an extension of electricity by utilising the excess power to supply the nearby surrounding communities for various uses [21].

2.3 Excess solar energy

Renewable energy sources, such as solar, have the potential to generate excess energy beyond immediate consumption needs [22]. The term "excess solar energy" typically refers to the surplus energy generated by a solar power system that is not immediately consumed by the end-use devices or stored for later use. When the sun is shining strongly and demand is low, photovoltaic systems can produce more electricity than is required [23].

Nevertheless, inefficiently utilising excess solar energy can result in various disadvantages, including economic inefficiency and environmental concerns. Firstly, when photovoltaic systems generate excess solar energy that goes unused or remains not stored, it signifies a wasteful depletion of valuable resources. This untapped energy could have been harnessed for productive purposes, thereby reducing the necessity for other energy sources [24]. Secondly, underutilisation of surplus energy can strain the electrical grid, potentially leading to voltage instability and grid congestion, which in turn could disrupt electricity supply [25]. Thirdly, economic value is lost due to missed opportunities for cost savings or revenue generation. If excess energy is neither stored nor sold back to the grid (in regions permitting net metering), the full economic advantages of solar power may remain unrealized [26].

Fourthly, inefficient utilisation of solar energy can indirectly contribute to environmental concerns. For example, when solar energy isn't effectively harnessed, there may persist a reliance on fossil fuels, which emit greenhouse gases and contribute to climate change [27]. Fifthly, failing to optimize excess solar energy utilisation compromises energy security. Solar power has the potential to enhance a region's energy independence by reducing reliance on external energy sources, but this potential benefit diminishes when excess energy isn't managed effectively [28]. Lastly, in regions with high levels of solar energy penetration, not utilising excess energy can hinder the integration of renewables into the energy mix. Efficiently storing or using surplus energy can improve grid stability and accommodate a greater share of renewable sources [29].

2.3.1 Utilisation of Excess Solar Energy

Efficient utilisation of surplus energy generated from renewable sources can significantly enhance the sustainability of energy systems [30]. One method involves thermal energy storage, where excess electricity is converted into heat and stored using technologies such as molten salt or phase-change materials [31]. This stored thermal energy can then be applied for heating, industrial processes, or electricity generation when renewable energy output is low. Additionally, demand response strategies encourage consumers to shift their electricity usage to times of high renewable generation, achieved through mechanisms like time-of-use pricing or smart grids, as explored in various research studies [32].

These strategies not only reduce the wastage of clean energy but also enhance the overall efficiency and stability of the energy system [30, 31, 32]. Despite the benefits, challenges persist, particularly concerning the efficiency and cost-effectiveness of energy storage technologies. The research underscores the critical importance of advancements in storage technology for effectively harnessing and utilizing excess renewable energy on a larger scale [33].

2.3.2 Exemplary Use of Excess Solar Energy

In various regions around the world, the innovative utilisation of excess solar energy has been at the forefront of sustainable development initiatives.

Across a spectrum of case studies, researchers have demonstrated diverse and impactful applications for surplus solar energy generated by solar milling plants. One research illustrated the stability achieved in milling operations through energy storage, ensuring consistent production even during cloudy periods or after sunset [34]. Other studies emphasized the significance of agricultural sustainability by showcasing a solar milling plant in Sub-Saharan Africa that employed surplus energy to power irrigation pumps, benefiting both milling and farming activities [35].

UNDP's documentation of an initiative in Mali highlighted community empowerment as excess solar energy was repurposed to charge portable battery stations, enhancing communication, extending productivity hours, and fostering small-scale entrepreneurship [36]. In India, a research study examined community microgrids powered by surplus solar energy from milling plants, demonstrating rural electrification's potential to improve quality of life, support local businesses, and promote economic growth [37]. Another study addressed the critical need for clean drinking water in Senegal and Mali by redirecting excess solar energy from milling plants to power water purification systems [38].

Developed countries integrated surplus solar energy into the grid, enabling energy trading and contributing to revenue generation and grid stability [39]. A case study was undertaken in South Asia where excess solar energy enhanced value-added processing activities at a rice milling facility, reducing reliance on grid electricity [40]. Other researchers illustrated a community-driven approach in Latin America, where excess solar energy charged portable battery packs for household appliance use during the evening, benefiting the local community [41].

Furthermore, studies demonstrate economic empowerment in Southeast Asia by using surplus solar energy to power small-scale coconut oil extraction units, enhancing productivity and reducing operating costs for microenterprises [42]. Lastly, another study focused on addressing food scarcity challenges in East Africa, where excess solar energy was harnessed to mill grains for fortified food products, promoting food security in the region [43].

2.3.3 Establishment of a Business hub using excess solar energy from SMPs.

Establishing a business hub powered by renewable energy in rural areas offers significant economic and social advantages for local development and sustainability. Renewable energy sources provide a reliable and continuous power supply, fostering business growth and job creation. Research studies highlight that implementing renewable energy systems in rural areas enhances energy security and stimulates economic growth by attracting investments and supporting entrepreneurship [44].

Solar energy is a particularly promising avenue for creating a successful rural business hub. Solar panels can be strategically placed on rooftops or in open areas to generate electricity, reducing reliance on centralized fossil fuel-based power generation. This aligns with the findings of other studies that emphasise the potential of solar microgrids in rural areas not only for electricity provision but also as platforms for small businesses and community activities [45]. Furthermore, the concept of a business hub extends beyond energy generation. Integrating energy-efficient technologies and sustainable practices into the hub's design and operations, as discussed further, can enhance its environmental and economic sustainability. This may involve adopting green building designs, implementing waste reduction strategies, and promoting local products and services, creating a holistic approach to rural development through renewable energy-powered business hubs [46].

Another recent study describes an expansion of this concept, where an energy hub was implemented in a Kenyan village. This hub serves as a central facility for charging rented solar lanterns and mobile phones. Additionally, it offers various centralised services like photocopying, typing, hairdressing, and television access [47]

2.4 Solar water pumping system

Solar water pumps (SWPs) are a clean, modern irrigation solution that has the potential to improve livelihoods and food security for smallholder farmers across Sub-Saharan Africa. As small-scale SWPs become more affordable, this market is poised for growth [48].

The utilisation of Solar Water Pumping (SWP) systems has evolved significantly in recent years [49]. These systems, powered by solar photovoltaic panels, have experienced substantial technological advancements, expanding their capacity and capabilities. Early solar pumps faced limitations in performance and were primarily suitable for shallow water sources and low water demand situations [50]. However, contemporary solar pumps can reach depths of up to 500 meters [51], revolutionising their applicability. Currently, the highest demand for SWP systems is found in interior rural off-grid areas, addressing underserved regions. These systems find diverse applications, including providing potable water for institutions, supporting community-scale water supply schemes, facilitating livestock water supply, and enabling small-scale irrigation [48, 51].

Solar pumping offers several advantages, as demonstrated in various studies. Economic viability has been established, with life cycle cost analysis (LCA) showing that solar PV pumping systems are more cost-effective than diesel engine pumping systems [52]. SWP systems reduce dependence on fuel and operate using freely accessible sunlight, circumventing challenges associated with weak or costly rural fuel supply networks [53]. Furthermore, these systems produce clean energy with minimal or no exhaust emissions and pollutants, ensuring environmental sustainability. They are known for their durability, reliability, and low maintenance requirements, unlike their diesel counterpart. SWP systems are modular and easily scalable to match varying power needs, providing flexibility. Safety is enhanced through system voltage regulation, minimizing fire risks [54].

Research studies have also examined the economic viability of PV water pumping systems, emphasizing the importance of accurate economic assessment. Cost-benefit analyses have considered both capital and operational costs, as well as broader socioeconomic impacts beyond financial gains. Case studies have explored the cost savings associated with reduced diesel consumption for irrigation, increased crop yields, and income for farmers [55]. Additionally, research has assessed the financial feasibility of solar water pumping systems for agricultural irrigation, analyzing factors like payback period and net present value. The social impact of SWP systems on rural communities has also been studied, highlighting improvements in living conditions, agricultural productivity, and local empowerment [56].

Despite these advantages, SWP systems face challenges, including high initial capital costs, although prices are decreasing. Storage solutions like water tanks can be expensive, and maintenance may require specialised technicians/providers, though accessibility is improving.

Theft of solar panels can be addressed through community awareness and antitheft measures. SWP systems can lead to excessive groundwater extraction due to near-zero marginal pumping costs [53]

The basic configuration of SWP systems relies on solar energy conversion to electrical and mechanical energy, powering an electric water pump that draws water from a borehole into a reservoir as shown in Figure 1. The system's performance depends on various factors, such as seasonal variations in solar radiation and changes in the pumping head due to fluctuations in water levels). Proper sizing algorithms consider these variables over the course of a year to ensure accurate system design [57].

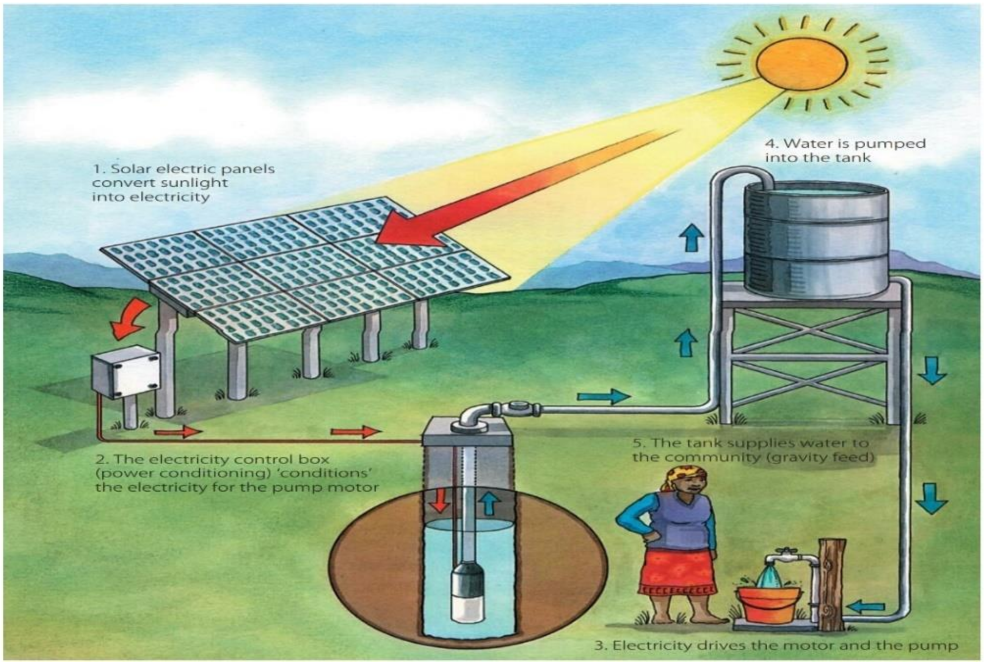

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Figure 1: Solar water pumping system. Image credit: Energy and Development Group [57].

2.5 Water requirements sizing

Water requirements sizing refers to the process of determining the optimal amount of water needed for a particular purpose or application. It involves calculating the quantity of water required to meet specific demands efficiently and effectively while considering factors such as location, climate, usage patterns, and available water sources [58].

2.5.1 Water requirements for home consumption

What is to be considered an adequate basic demand for water depends on the user habits as well as on climatic and cultural conditions. In rural Zambia, a sufficient basic supply can be achieved with 20 to 40 litres per person per day. The Zambia Bureau of Standards has adopted the following guidelines for residential water demand for formal and informal housing areas; informal or rural housing requires 40 litres per person per day, low-cost housing needs 100 litres per person per day, medium-cost housing requires 150 litres per person per day and high-cost housing requires 280 litres per person per day [59].

2.5.2 Water requirements for irrigation

The combination of hot, dry, and windy conditions will cause rapid water loss from soil and plants. If excessive soil drying occurs during a critical water-need period, the yield can be significantly reduced. Irrigation must be able to supply water at the expected peak water use rate to be successful during rainfall-deficient periods. The peak water use rate for vegetables and most grain crops falls between 5 to 6 millimetres per day (21000 to 26000 litres per acre per day). The peak water use rate for high-yielding grain corn can reach 8 millimetres per day (34000 litres per acre per day) [60].

2.5.3 Water requirements for Chicken poultry

Sizing water requirements for poultry farming is crucial to ensure the well-being and productivity of the birds. Water is essential for various physiological processes, including digestion, temperature regulation, and overall growth. The water needs of poultry can vary based on factors such as age, size, environmental conditions, and type of production system. [61].

According to studies, there are recommended guidelines for estimating water requirements in poultry farming [62]. For broiler chickens, the water intake can be estimated based on body weight. Researchers suggest that broilers consume approximately 1.6 to 2.0 times their body weight in water per day. For example, a broiler chicken weighing 2.5 kg might require around 4 to 5 litres of water daily. It's important to note that during hot weather or when using high-energy diets, water intake might increase. Layer hens, on the other hand, have slightly different water requirements [62]. Other studies recommend that laying hens consume approximately

2.5 to 3 times their feed intake in water. Therefore, if a laying hen consumes 120 grams of feed per day, it might require around 300 to 360 millilitres of water [63].

In addition to body weight and feed intake, environmental factors play a significant role in water needs. High temperatures, humidity, and dry conditions can increase water consumption, as birds need water for thermoregulation and to avoid heat stress. To properly size the water supply system for a poultry farm, it's essential to consider the estimated water requirements based on the factors mentioned above. Providing adequate access to clean and fresh water is essential for maintaining the health and productivity of poultry [62,63]. Water requirements are related to feed consumption and air temperature. Over half of the water intake of poultry is obtained from the feed. Automatic watering equipment ensures poultry have free access to water at all times.

Once air temperatures exceed 30°C, the expected water consumption can increase by 50 % above normal consumption rates. Poultry is unable to sweat as a means of regulating body temperature. Their method of heat control involves increasing the respiratory rate (panting) to expel surplus heat, which results in the release of large amounts of moisture from the bird that must be replaced or the bird will become dehydrated. An estimate of the daily water consumption of 1,000 broiler chickens at different stages of growth shows that a chicken broiler at the age of 1 to 4 weeks needs 50 to 260 litres of water per 1000 birds per day at 21°C and 50 to 515 litres of water per 1000 birds per day at 32°C. Furthermore, a Chicken broiler at the age of 5 to 8 weeks needs 345 to 470 litres of water per 1000 birds per day at 21°C and 550 to 770 litres of water per 1000 birds per day at 32°C [61].

Another estimation of daily water consumption is for other common classes of chickens other than broilers. Once more, temperatures have a major influence on the water consumption rate expected from these other poultry classes. Egg production level will also affect the water consumption of laying hens. It has been estimated that laying hens will drink about 4 kg of water per dozen eggs produced. The water consumption is as follows; laying hens require an average of 250 litres of water per 1000 birds per day, pullets consume 105 litres of water per 1000 birds per day and broiler breeders need 250 litres of water per 1000 birds per day [61].

2.6 Water, Energy and Food (WEF) nexus

Granting the definition of the water-energy-food nexus may vary across different sources, the foremost idea is that water, energy and food sectors are interconnected and the security of one of them depends on the other two [62]. WEF nexus approach starts with consideration of interlinkages through the whole system and then looks at the two-way interlinkages among water, energy, and food individually. Amid the pressure from population growth, climate change, globalization and urbanization, the nexus approach can be used to increase the efficiency of the whole system, build synergies and minimize trade-offs between sectors [63].

WEF nexus is defined as an approach that integrates clean water supply, irrigation, and agro and fish-processing activities, to capture different types of value. Needs-based irrigation increases food producers' resilience against droughts and breaks the cycle of seasonal income, just as ice production allows for a more efficient value chain for fish production. Such processing services can lead to a more stable income generation and diversification of economic activity. The availability of clean water improves the quality of life and health conditions in a community [64]. The WEF nexus is further described in Figure 2.

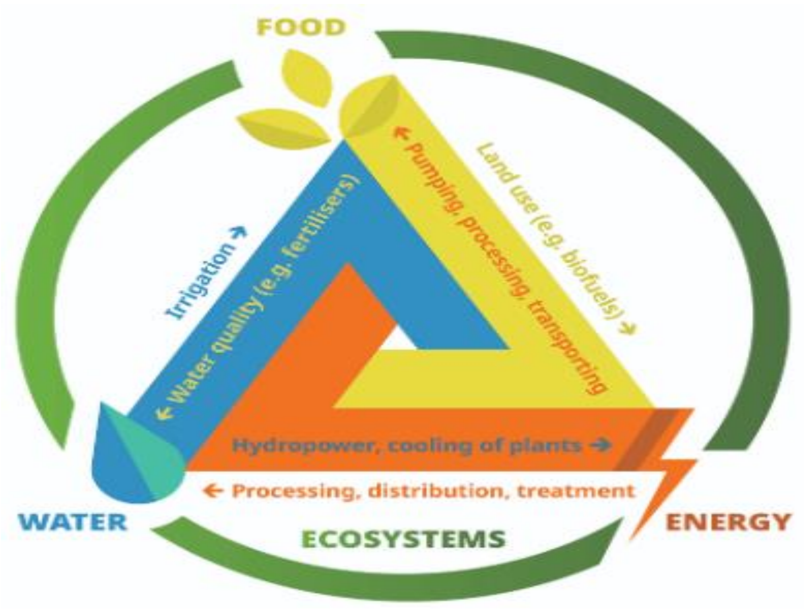

Figure 2: The WEF nexus approach [64].

The above figure can be explained as a multi-dimensional interlinkage between WEF and the ecosystem.

(i) Water plays a vital role in energy production, e.g., in hydroelectric plants, for cooling thermal (fossil-fuel or nuclear) plants and in growing plants for biofuels. Conversely, energy is required to process and distribute water, treat wastewater, pump groundwater and desalinate seawater.

(ii) Water is also the basis for the entire agro-food supply chain. Equally, agricultural intensification impacts water quality.

(iii) The third interlinkage is between energy and food. Energy is an essential input throughout the entire agro-food supply chain, from pumping water to processing, transporting and refrigerating food. Conflicts around land use for food production may arise in the case of biofuels or extended solar installations [63].

Healthy ecosystems are an essential requirement for the sustainability of all the above and are negatively affected if water, energy or food are used in an unsustainable way.

2.6.1 The cost and mitigation of WEF nexus

Supposing water and food-related energy demands helps to drive the economic sustainability of off-grid projects by supporting energy consumption [65], the WEF nexus approach comes at a cost. The benefits and risks of both corporate and market should be assessed [66]. To date, energy investments in mini-grids with a full equity structure are not viable, and governments struggle to support them because of public energy companies' poor balance sheets and political priorities, which are often linked [67]. Rural electrification alone will not be able to support local development and create energy demand [68]. However, if rural electrification is integrated with investments along the food value chain and other productive uses of energy, it can bring substantial development outcomes and consequently entice the attention of governments, international development agencies, and investors [69]

2.6.2 The main challenges of the WEF nexus from an environmental, economic, and social perspective?

The WEF nexus is challenging primarily because of the impact of environmental factors such as climate change, degradation of ecosystems, and pollution; and the growing demand for WEF, which is caused by economic and social factors such as population growth, economic growth, urbanization, change in food habits, expansion of global trade, and technological advances [70]. Though the challenges were divided into three categories – environmental, economic, and social, these challenges are connected and can cause a chain reaction. For instance, economic growth speeds up urbanization, which may further cause pollution of water resources and ecosystems [71].

Additionally, private developers face the major challenge of having to reach the bottom of the pyramid, characterized by low income – often below the poverty line – and low energy consumption, limited ability to pay for energy services, and mostly vulnerable to environment, social, and economic threats [72]. Reliable and affordable electricity directly influences the productive capacity and resilience to extreme events of rural populations; it can power small and medium-scale rural enterprises, increasing their contribution to job creation and income generation as well as improving living conditions in rural areas. Electricity consumption and economic growth have gone hand-in-hand since the beginning of the last century and today it's more important than ever to recognize this relationship [73].

Furthermore, rising temperatures will bring higher demand for water for irrigation. Livelihoods can be affected by expanding shortages of drinking water. Another environmental challenge is the degradation of ecosystems which affects runoff, groundwater discharge, water quality and availability. Pollution of water resources from fertilizers can be an issue as consumption and production have been increasing. Economic factors such as economic growth, expansion of global trade, and technological advances are all leading to the growth in demand for water and energy. The rise in incomes and higher demand for products requires expanding production and higher use of energy, while food production both for domestic consumption and export requires more water. Social factors such as population growth, changes in food habits, and urbanization also lead to a higher demand for water, energy, and food. Adding to the growing number of consumers, their diets and preferences are changing as a result of growing incomes [70]. More food needs to be produced, and food production can become more water-intensive because of the shift to animal-based diets [75].

2.3 Solar PV system components

The terminology and components associated with photovoltaic (PV) systems play a crucial role in understanding the technology, design, and implementation of solar energy solutions [76]. Below are the definitions of PV systems components useful in understanding the design process recommended in this study:

2.3.1 Solar Module

A solar module is a single photovoltaic panel that is an assembly of connected solar cells. Solar cells absorb sunlight as a source of energy to generate electricity. The solar cells' efficiency and wattage output can vary depending on the type and quality of solar cells used. A solar module can range in energy production, the higher the wattage output, the more energy production per solar module. A solar array of modules consisting of higher energy-producing solar modules will, therefore, produce more electricity in less space than an array of lower-producing modules [77].

2.3.2 Charge controllers

Charge controllers, also known as charge regulators, are essential components in PV systems that manage the flow of electric charge between solar panels and batteries. They prevent overcharging and undercharging of batteries, enhancing battery lifespan and system efficiency. Charge controllers ensure that energy generated by solar panels is optimally stored in batteries for later use [78].

2.3.3 Maximum power point tracking (MPPT) Solar Charge Controller

These are Morden solar charge controllers which maximize energy harvest by driving it intelligently to batteries to achieve full charge in the shortest possible time. Smart Solar maintains battery health, extending its life. Maximum power point tracking (MPPT) is the ultimate in controllers with efficiencies in the 94 % to 98 % range. The major unique principle of MPPT is to extract the maximum available power from the PV module or array, by making them operate at the most efficient voltage (maximum power point). This voltage is matched to the battery voltage, to ensure maximum charge (amps) [79].

2.3.4 Inverters

A solar inverter or PV inverter is a type of electrical converter which converts the variable direct current (DC) output of a photovoltaic (PV) solar panel into a utility frequency alternating current (AC). It is a critical balance of system (BOS)–components in a photovoltaic system, allowing the use of standard AC-powered equipment. Solar power inverters have special functions adapted for photovoltaic arrays, including maximum power point tracking and anti-islanding protection [80].

2.3.5 Hybrid Inverters

Hybrid inverters also referred to as multi-mode inverters, represent advanced power electronic devices employed in renewable energy systems, particularly within solar energy installations. These inverters are purpose-built to operate seamlessly with both solar panels and energy storage systems, such as batteries, offering several advantages, including energy usage optimization, enhanced system efficiency, and the provision of backup power during grid outages [81]. Here's a comprehensive overview of hybrid inverters:

Hybrid inverters are primarily designed for solar PV (photovoltaic) systems, efficiently converting the DC power generated by solar panels into AC power for household consumption or feeding it back into the grid. A key feature of these hybrid inverters is their compatibility with energy storage systems, typically lithium-ion batteries. They are capable of charging the batteries when surplus solar energy is available and discharging them when necessary, such as during nighttime or power outages [82].

Furthermore, hybrid inverters can function in grid-tied mode, where they feed excess solar power back into the grid, potentially earning credits or reducing electricity bills. They can also operate in off-grid mode, providing power to a residence or facility when there is no grid connection. Additionally, they can operate in grid-tied mode with a backup function, ensuring power availability during grid outages [83].

Some hybrid inverters are equipped with load management capabilities, empowering users to prioritize which loads are powered by solar energy, battery power, or the grid. This feature enables homeowners to maximize their consumption of solar energy while minimizing reliance on the grid. Hybrid inverters are meticulously designed to exhibit high efficiency in both the conversion of solar energy and the management of battery charging and discharging. This heightened efficiency significantly contributes to overall system performance improvement [84].

Many hybrid inverters come equipped with advanced monitoring and control features, accessible remotely via mobile apps or web interfaces. This capability allows users to monitor the system's performance and make necessary adjustments. Furthermore, certain hybrid inverter systems are modular, allowing users to expand their solar array or battery capacity over time to accommodate changing energy requirements. Moreover, hybrid inverters are engineered to comply with the grid interconnection standards and safety regulations specific to the region in which they are installed [85].

In some instances, hybrid inverters are integral components of larger hybrid energy systems that may encompass additional renewable energy sources, such as wind turbines or micro-hydro systems, thereby offering even greater energy flexibility [86].

2.3.6 Off-grid solar energy system

An off-grid solar system is designed for the power needs of mid-to-large-size homes. Unlike a grid-tie solar system, off-grid systems have no connection with the utility grid and must make all the electricity necessary for a home. Off-grid solar systems operate from the stored energy in a battery bank. Solar panels are used to keep the battery bank charged [87].

2.3.7 Solar Mini-grid

A mini-grid is a small-scale electricity network fed by solar energy. The generated electricity is supplied – directly or indirectly via batteries – to clients connected to this mini-grid electricity network. A mini-grid can be defined as a set of electricity generators and, conceivably, energy storage systems unified to a distribution network that supplies electricity to a local group of customers [88].

Mini-grids have an exceptional feature as they can operate autonomously without being connected to a centralized grid. However, the mini-grid may be designed to interconnect with the central grid, which means it works under normal circumstances as part of the central grid, with disconnection occurring only if power quality needs to be maintained, for instance, in the case of a central grid failure. Alternatively, a mini-grid may be designed to operate separately in a remote location with the option to connect to a central grid when grid extension occurs [75].

2.3.8 Utility-scale solar power plant

A utility-scale solar power plant refers to large-scale solar installations designed to generate a significant amount of electricity, often in megawatt (MW) or gigawatt (GW) capacities. These plants can be ground-mounted or integrated into rooftops and are typically connected to the central grid to supply electricity to a wide consumer base. A utility-scale plant generates solar power and feeds it into the grid, supplying a utility with energy. Virtually every utility-scale solar facility has a power purchase agreement (PPA) with a utility, assuring a market for its energy for a secure term of time [75].

2.3.9 Hybrid systems

Hybrid solar energy systems combine different renewable energy sources, such as solar and wind, with conventional energy sources and energy storage. These systems enhance reliability by ensuring a continuous power supply even when solar generation is reduced, allowing for optimization of energy resources [86]. Hybrid renewable energy systems (HRES) are becoming popular as stand-alone power systems for providing electricity in remote areas due to advances in renewable energy technologies and subsequent rises in the prices of petroleum products. A hybrid energy system usually consists of two or more renewable energy sources used together to provide increased system efficiency and a more outstanding balance in energy supply [75].

2.4.0 PV array sizing

The escalating demand for sustainable energy sources and environmental concerns have led to a significant rise in the adoption of photovoltaic (PV) systems. The sizing of photovoltaic (PV) array systems is a critical aspect of designing efficient and cost-effective solar energy installations. Properly sizing a PV array is essential to maximize energy generation and guarantee the economic viability of installations. To determine the optimal PV array size, the method of energy balancing is crucial in providing a framework for engineers and designers [89]

The energy balance method involves matching the energy generated by the PV array with the energy demand of the load. This approach considers factors such as solar radiation, system efficiency, and load profile. Studies present an energy balance approach for sizing PV systems in off-grid scenarios, ensuring that generated energy meets consumption needs [90]. Photovoltaic (PV) systems have garnered substantial attention as sustainable and renewable energy sources. Sizing a PV array correctly is paramount to optimize energy production and ensure the economic feasibility of these systems [91].

Theoretical methods encompass models for solar radiation, load profile analysis, and loss estimation. Solar radiation models are fundamental for assessing energy potential [91]. They offer precision in PV array sizing by considering location-specific factors and adaptation to varying load profiles, integrating environmental conditions, and enhancing system performance and efficiency [92].

2.4.1 Sizing an off-grid stand-alone photovoltaic power system

Using an energy balance method (EBM), sizing a photovoltaic system for a stand-alone photovoltaic power system involves a five-step process which will allow the photovoltaic system designer or user to accurately size a system based on users' projected needs, goals and budget. This method of sizing is well-suited for off-grid PV systems due to its ability to ensure that the energy generated by the photovoltaic array matches the energy demand of the load reliably and consistently. Off-grid systems operate independently from the utility grid, relying solely on the generated solar energy to meet the energy needs of the users. Here are the steps involved in sizing: Estimating the Electric Load, sizing and specifying an inverter, sizing and specifying batteries, sizing and specifying an array and lastly, specifying a Controller [89].

Computing the Daily Energy Demand (DED) is completed by determining the daily energy demand required by the user. This is done by talking to the user about their needs and plans to factor that into the design and sizing. The items can be tabulated as shown in Table 1.

Table 1: Details of the Load Requirements

Number of Rooms	Number of appliances	System voltage	Appliance rating power	Daily usage (Hrs)	Total power (W)	Daily energy demand (Whrs)

In Column 1, the place/room in the house where the light or appliance will be located is entered. Column 2 is for the number of appliances or lights per room that will be powered. Column 3 indicates the system voltage while the power rating of each appliance is entered in column 4. The estimated number of hours each appliance will be in use per day is in column 5. The total power for each appliance is obtained by multiplying column 2 and column 4 and the value entered in column 6. Lastly, the amount of energy needed for each appliance is obtained by multiplying the number in column 5 by that in column 6 and the product entered in column 7. The total power needed by all the appliances is the sum of the values in column 7. The content of column 7 is also summed up giving the total Daily energy demand (DED) for the user in Watt-hours (Whrs). Since system components are never ideal, about 25 % loss is considered for margin error and it is added to the total in column 7 to get the final DED in Whrs.

The battery bank capacity (Ahrs) needed in a day is determined by the total energy needed from the batteries in a day. To calculate the battery bank capacity, the DED in Ahrs is multiplied by the days of autonomy (the number of days to have energy supply from the batteries when there is no sunshine-usually about 3) and this is divided by the depth of discharge (DOD), (how much energy you can safely use from the battery to avoid excess draining) as a decimal. Some designers prefer a DOD of 50 % (0.5) and others 20 % (0.2). it must be noted that the lower the %age of DOD, the larger will be the battery bank. Firstly, the battery size (rating) is chosen from what is available in the market. Secondly, is the determination of the number of batteries in parallel strings by dividing the battery bank capacity (Ahrs) by the rating of the battery chosen (Ahrs). The third step is to determine the number of batteries connected in series. This is done by dividing the system voltage by the voltage of one single chosen battery. Lastly, to get the total number of batteries needed, multiply the number of parallel strings by the number of series-connected batteries in each parallel string [90].

CHAPTER 3: METHODOLOGY

3.1 Introduction

Visits to six selected solar milling plants in Eastern Province were undertaken. The average daily energy generated, energy consumed, and excess unutilised energy were investigated and recorded. A household and technical questionnaire was designed and administered to evaluate the community's needs. Excel and statistical packages for social sciences (SPSS) were used to analyse and interpret the collected data. Finally, a concept design for a solar water pumping system and a business hub around the SMP was recommended to benefit the local communities.

3.2 Research design

A survey approach was used in conducting this research. This involved collecting data by interviewing a sample of people selected to represent the population under study. This study was mainly deploying qualitative and quantitative methods of data collection. Two structured questionnaires were used to collect data. One was for the community energy needs assessments, and the other was for REA, ZCF and SHM workers on the generated energy profile, load profile and surplus energy profile.

3.3 Target population

The research study targeted the people working at solar milling plants, ZCF officers, REA officers and all households within a 500 m radius surrounding the solar milling plants. The target province was the eastern province particularly, Petauke, Chipata and Lundazi.

3.4 Sample and sampling techniques

Random sampling and purposive sampling were employed to select respondents. Systematic random sampling was used to select respondents from the community. Purposive sampling was used to determine critical informants such as community representatives, facilitators/ millers, respondents and REA officers. In addition, a sample size of an average of 25 respondents was selected to participate in the study, and all were given questionnaires to respond to. Eighty respondents from the village, five community representatives, three from REA, three ZCF officers and five from the milling plant were sampled. This sample size was chosen because it was cost-effective, manageable and adequate for generating precise data. Therefore, the study comprised both males and females regardless of their status, race and religion. Hence, the results of this study would depend on the accuracy and authenticity of the information provided by the respondents.

3.5 Data Collection

The study was carried out in Lundazi, Chipata and Petauke of Eastern Province, as shown in Figure 3. Primary data was collected from the respondents' answers on structured questionnaires and structured interview schedules, also by measuring the generated energy profile, load profile and surplus energy profile of SMPs. Primary data is vital for this study because it got information directly from the people on the ground. In addition, Secondary data was also used for this study, including published research findings of previous studies and other published documents such as articles, journals relating to the research topic, and the internet. This is important for this study because it brought to light areas of study that have been conducted about the subject under research and also shows the extent of such study. Therefore, Secondary data was fundamental because it helped to highlight the gaps in the previous studies, which, hopefully, this study seeks to fill.

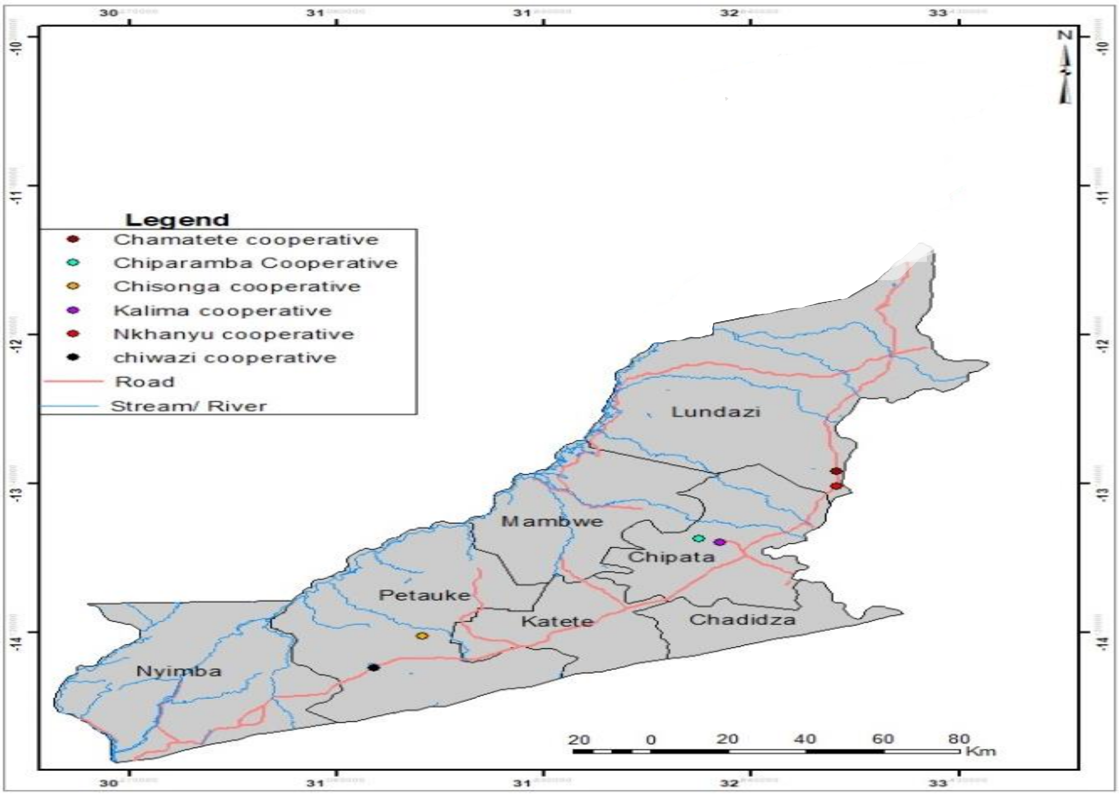

Figure 3: Shows the map of Eastern Province (study area)

3.6 Questionnaires

Two structured questionnaires were used to collect data. One was for the community energy needs assessments, and the other was for REA, ZCF and SMP workers on the generated energy profile, load profile and surplus energy profile.

The research tool comprised open and closed-ended questions. Furthermore, it was supposed that the facilitators could read and write. Thus, there was an effective response to self-administered questionnaires. However, for respondents who were unable to read and write, both unstructured and structured interview schedules were utilized. In this instance, the advantages of using interviews rather than self-administered questionnaires include accuracy and completeness of the interview schedules, high return rate of the data required and avoiding time-wasting. Further, during interviews, a researcher could explain to the respondents the meaning of questions and repeat them, if necessary, for respondents to clarify the information being asked.

3.7 Data Analysis

Editing was done after collecting data to eliminate errors by checking on completeness, accuracy and uniformity. Thus, errors were corrected, and responses were put in the right place.

After collecting the data, coding followed to ensure that all values and variables under study were correctly captured. The data collected from the questionnaire was to be checked for uniformity, consistency and accuracy. Questions were coded for ease of data analysis. Analysis and interpretation of data were made with the help of computer software and statistical tools such as Microsoft Excel (MS Excel) and Statistical Package for Social Science (SPSS) version 16.0.

3.8 Ethical Consideration

Ethics in this research study was highly considered by the researcher seeking informed consent from the participants and disclosing the research aims. Voluntarism was also considered, as participants were not forced or coerced to participate in the study. Furthermore, confidentiality was assured as the participants were not allowed to indicate their identities or names on the questionnaire. Data from participants were kept confidential to protect respondents from any psychological or physical harm and danger against their participation in the study.

3.9 Limitations of the Study

One limitation of this study was the insufficient availability of historical performance and technical data on SMPs at a significant level, which posed challenges for both policymakers and researchers. Another limitation was the high levels of illiteracy among members of the cooperatives. This necessitated simplifying the questions for the respondents to ensure that they could understand and provide accurate answers. However, this situation may have potentially led respondents to provide biased responses due to interviewer guidance, which could have somewhat compromised the quality of the collected information. The last limitation related to funding, which indirectly led to restrictions on the number of site visits that could be conducted and the limited amount of time that could be spent on each site.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Technical configuration and performance

Sunlight was used as the sustainable energy source, and a photovoltaic system was used to operate a stationary SHM. A SMP consists of three main parts as illustrated in Figure 4:

i) Solar panel station, which generates the energy needed to run the milling machine.
ii) The control room contains switches and capacitors which store energy for a short period and condition the flow of that energy to the SHM. Capacitors can supply power for brief periods when there is a temporary fluctuation in solar energy generation or to handle short bursts of high-power demand and help stabilize voltage levels.
iii) SHM also contains a Switch for controlling the machine's operation by turning it on and off.

The milling machine operates by solar energy from about 09 hrs to about 15 hrs, and maize is one raw material milled by this milling machine. There are three types of SHMs installed in Zambia, namely first-generation, second-generation and third-generation.

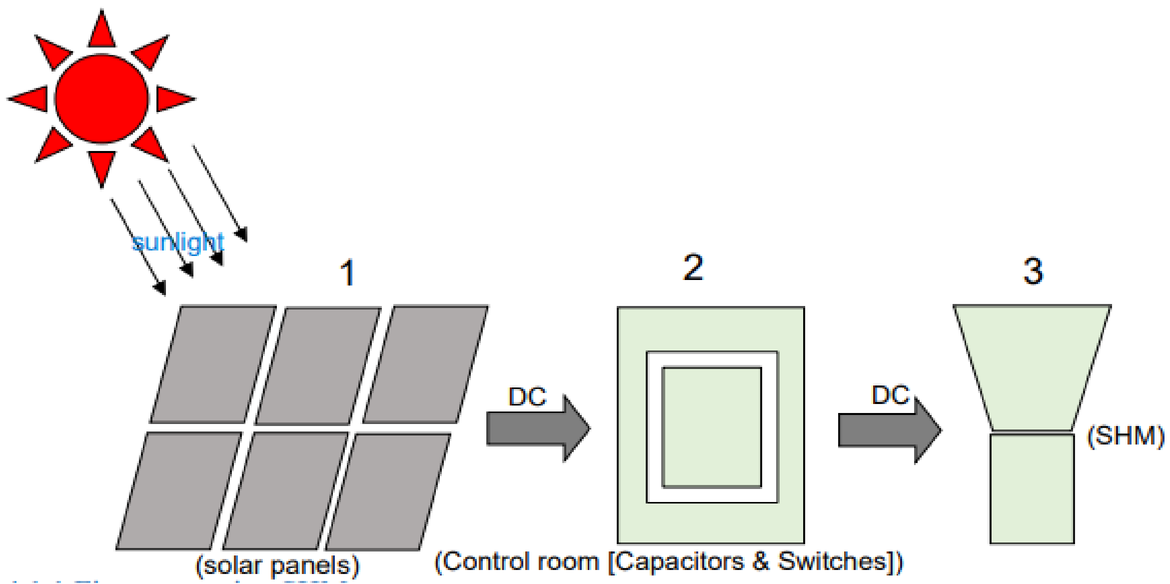

Figure 4: SMP current configuration

4.1.1 First-generation SHM

First generation SHM is a 15 kW plant connected to 60 polycrystalline solar panels. It uses approximately 7 kW maximum and 5 kW minimum power to start the operation. It is manually operated, with all the adjustments being purely mechanical, and it has three big DC motors which drive the whole system. The first motor is the hammer mill motor which initiates the grinding process by powering the hammers, the second one is the material transport motor which moves the milled material to the desired location. The third one is the extractor or separator motor ensures proper separation and collection of the milled material. Each DC motor connects to the main components respectively, and these are the engaging lever, adjusting knob and extractors. These parts work together in unison to contribute to the control, customization, and efficiency of the milling process. The engaging lever starts and stops the grinding operation, the adjusting knob regulates particle size, and the extractor ensures the effective separation and collection of the milled material (only the intended milled material is collected), while contaminants or fine particles are properly filtered out. The pneumatic circuit of a solar hammer mill (used to convey materials to be milled) typically uses ambient air, which is compressed for various tasks in the milling process. The compressed air helps control and automate different aspects of the hammer mill operation, contributing to its efficiency and functionality. Figure 5 shows a picture of the first-generation machine

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Figure 5: first-generation SHM machine.

4.1.2 Second-generation SHM

The second-generation SHM (as shown in Figure 6) has a 12.5 kW power station with 50 polycrystalline solar panels. Similarly to a first-generation, Bank capacitors are used to store power for a short period. Its minimum power to operate is 3kW which shows a reduction from the 5 kW minimum for the first-generation. This version is automated with many sensors on roller mills but has the same extractors as the first generation. It has small motors, and each motor performs a specific function. There is no adjusting of the lever and knob. It uses pneumatic fans and an interface for digital commands. The interface typically consists of a display screen, buttons, switches, and indicators. It can be a touchscreen panel or a combination of physical buttons and a digital screen. The components are designed to provide a user-friendly way for operators to input commands and receive feedback. Operators use the interface to interact with the hammer mill system. They can input commands, adjust settings, and initiate specific functions through the digital interface. The types of commands and functions available on the interface include:

(i) Start and Stop: Operators can initiate and halt the milling process using dedicated buttons. This could involve starting the hammer mill motor, material transport system, and extractor mechanism.

(ii) Adjustment of Grinding Settings: The interface might allow operators to adjust parameters such as the speed of the hammer mill motor or the gap between grinding plates. This can be crucial for achieving the desired particle size in the milled material.

(iii) Monitoring and Feedback: The interface can provide real-time information and feedback. It might display information such as current power generation from the solar panels, motor speed, energy consumption, and temperature levels.

(iv) Safety Features: The interface can include safety features, such as emergency stop buttons or indicators that alert operators to potential issues or anomalies.

(v) Digital Control and Integration: The digital interface is connected to the control system of the solar hammer mill. It communicates with various components, such as motor control systems, sensors, and feedback mechanisms. Digital commands entered by operators are translated into control signals that direct the operation of different motors, mechanisms, and processes within the hammer mill.

Figure 6: Second-generation SHM machine with an operator standing next to it.

4.1.3 Third-generation SHM

The research shows that the third generation is similar to the second-generation, with a slight difference. It is automated but has a mechanical difference; it does not use pneumatic fans like the second generation but has elevators to lift or convey materials. Figure 7 shows a third-generation machine.

Figure 7: Third-generation SHM machine

4.1.4 Comparative analysis difference between the SMPs generations (summary table)

Table 2: Shows the summary of the Comparative analysis difference between three generations of SMPs

	1st generation	2nd generation	3rd generation	Narrative
SMP power capacity	15 kW	12.5 kW	12.5 kW	The 1st generation has a higher power capacity than the 2nd and 3rd generations.
Minimum power consumption	5 kW	3 kW	3 kW	The 1st generation is disadvantaged because it cannot work with little solar power (less than 5kW). In contrast, the 2nd and 3rd generations can work with a minimum power of 3kW.

Number of panels	60 panels	50 panels	50 panels	-
Type of panels	Polycrystalline	Polycrystalline	Polycrystalline	
Operations	It is manually operated with three big DC motors, which operate the whole system. It uses pneumatic fans or air to convey materials. (It is purely mechanical)	This version is automated with many sensors on roller mills. There is no adjusting of the lever and knob, and it uses pneumatic fans and an interface for digital commands.	This version is also automated but does not use Air pressure but has elevators to lift materials or convey materials	The 1st generation takes too long to charge the bank capacitors, and because of too much mechanical adjustment during operation, the machine may be destroyed.
Environmental regulation	It is clean because of using pneumatic or air to convey materials	It is clean because of using pneumatic or air to convey materials	It is not clean because of the use of mechanical elevators to convey materials	The 1st and 2nd generation keeps the environment clean.
A mechanical system (design)	Same separation system with 2nd generation (extractors)	The same separation system with first-generation (extractors)	Extractors use Box mini-sister.	The 1st and 2nd generation takes too long, a minimum of 2hrs during maintenance

				to change the sieve, while the 3rd gen. takes only 20mins

4.2 Average energy generated, energy consumed and excess unutilized energy of selected SMPs

The maximum power recorded, for example from the first-generation SMP is 15 kW, with a maximum utilised power output on average at 5.5 kW during operation and 8.5 kW average excess power. On average, the maximum amount of irradiance recorded was 939 W/m^2 (from Table 3) which is 94 % closer to the maximum normal surface irradiance of approximately 1000 W/m^2 at sea level on a clear day. Figures 8 and 9 illustrate the behaviour of power and irradiance against time, respectively.

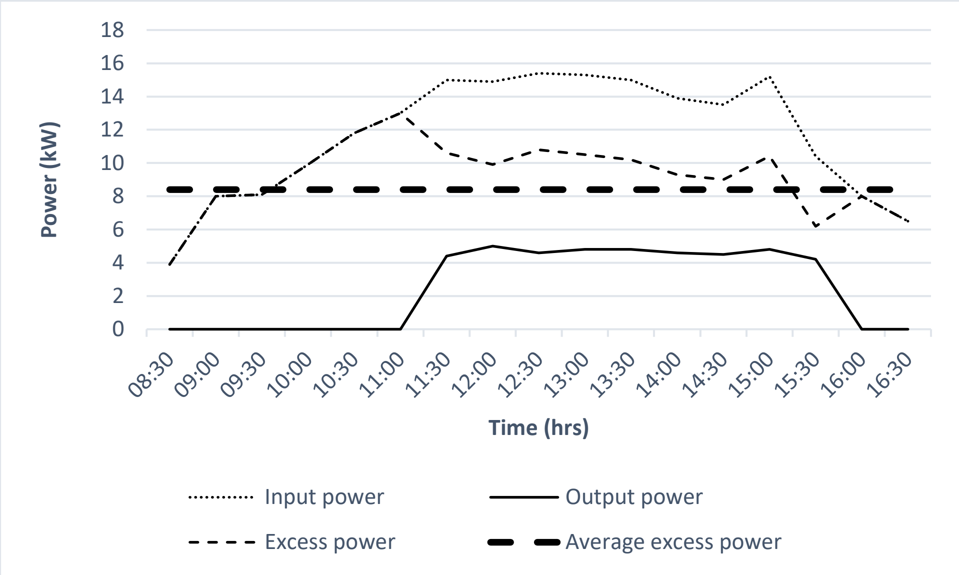

Figure 8: Behaviour of input solar power, output solar excess power, and average excess power during the day. Location of SMP: Kalima cooperative, Chipata

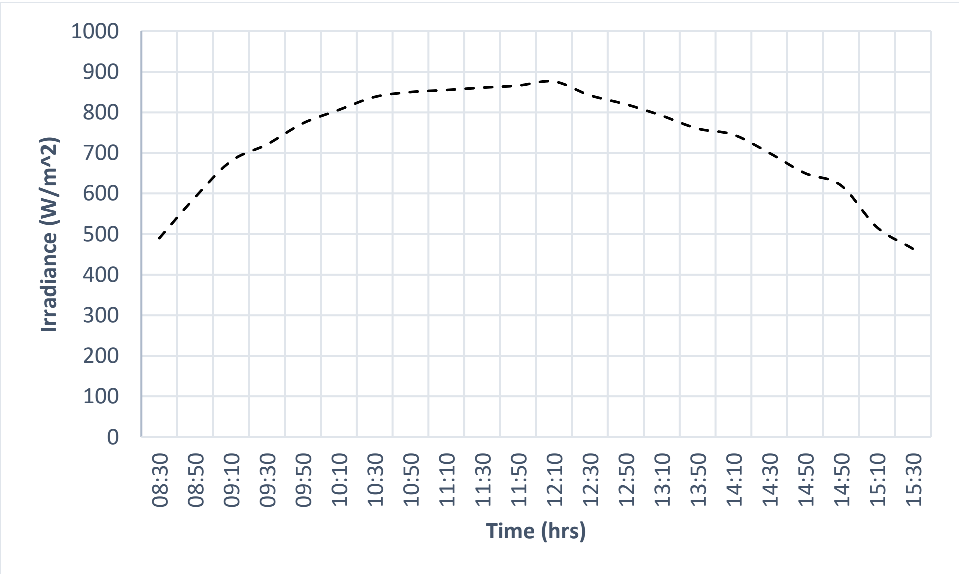

Figure 9: Irradiance against time. Location: UNZA SEC. Sep.2022

According to Figure 8, SMPs are usually active between 09 hrs and 16 hrs and this can be explained by the amount of irradiance available during the same period. Irradiance determines the amount of energy falling on solar panels as illustrated by Figure 9 (take note: Despite the location where irradiance was measured being in a different place, its behaviour against time is generally the same throughout the country). Over the course of the day, the power of the sun (irradiance), increases, peaks, and then drops.

Table 3: Average energy generated, energy consumed and excess unutilized energy of selected SMPs

Name of Site	No. of solar panels	Panel rating (Polycrystalline)	Maximum energy generated	Maximum energy utilised	Maximum excess energy	Average Excess energy	Maximum irradiance (Month of September 2021)
Kalima cooperative, Chipata	60	250 W_p	15.0 kW	5.0 kW	13 kW	8.5 kW	960 W/m^2
Chiparamba Cooperative, Chipata	60	250 W_p	14.6 kW	5.7 kW	12.7 kW	9.0 kW	1000 W/m^2
Nkhanyu Cooperative, Chipangali	60	250 W_p	15.0 kW	5.3 kW	11.0 kW	10.3 kW	850 W/m^2
Chamatete cooperative, Lumezi	60	250 W_p	15.0 kW	6.2 kW	12.0 kW	9.2 kW	908 W/m^2
Chisongo Cooperative, Petauke	60	250 W_p	14.0 kW	4.8 kW	10.8 kW	8.5 kW	1001 W/m^2
Chiwazi Cooperative, Petauke	60	250 W_p	15.0 kW	5.7 kW	11.0 kW	8.6 kW	917 W/m^2

4.3 Population characteristics

The relevance of respondent marital status, level of education, annual income, and energy needs to renewable energy research studies lies in their potential to provide insights into the socio-economic and demographic factors that influence attitudes, behaviour, and adoption patterns related to renewable energy technologies. These factors can significantly impact the success and effectiveness of renewable energy initiatives. Below are the population characteristics that describe the population under study.

4.3.1 Kalima cooperative, Chipata

Location: The village is located along a tarred road in Kasenengwa area approximately 19 km from Chipata town.
Latitude: 13.52704633 **Longitude:** 32.52091829

4.3.1.1 Demographics

In the household survey, 29 households were interviewed, representing 100 % of the targeted population within a 500 m radius. The average household size was found to be six persons. Concerning marital status, 100 % of the respondents were married. Regarding education levels, 55 % of respondents had gone up to primary school level, 35 % attained secondary education, and 10 % had no educational background.

4.3.1.2 Sources of Income

The sources of income for households in the targeted load centres were established primarily from the household survey. It was established that most people in the area depended on farming. Among the families interviewed, 90 % reported earning most of their income from farming, while 10 % received income from farming and businesses. The average annual income was estimated at ZMW17, 000.00.

4.3.1.3 Current Utilised Energy Sources

It was established by the survey that households used multiple energy sources to meet their energy needs. The survey results for cooking/heating show that about 66 % used firewood, about 28 % used charcoal, and about 7 % used both firewood and charcoal, while for lighting shows that about 66 % used solar lamps, about 31 % used battery lamps, and about 3 % used other sources. Figure 10 and Figure 11 give an overview of the utilized energy sources and currently utilised lighting sources for the interviewed respondents respectively.

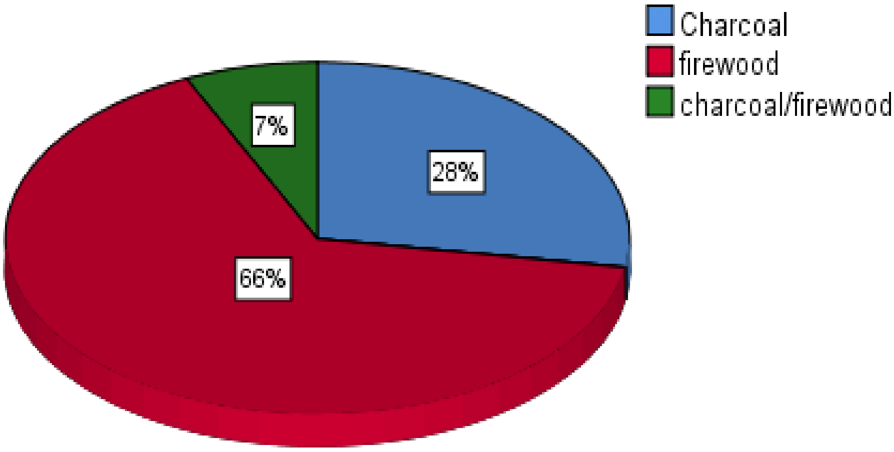

Figure 10: Currently utilised heating and cooking energy sources around Kalima cooperative in Chipata.

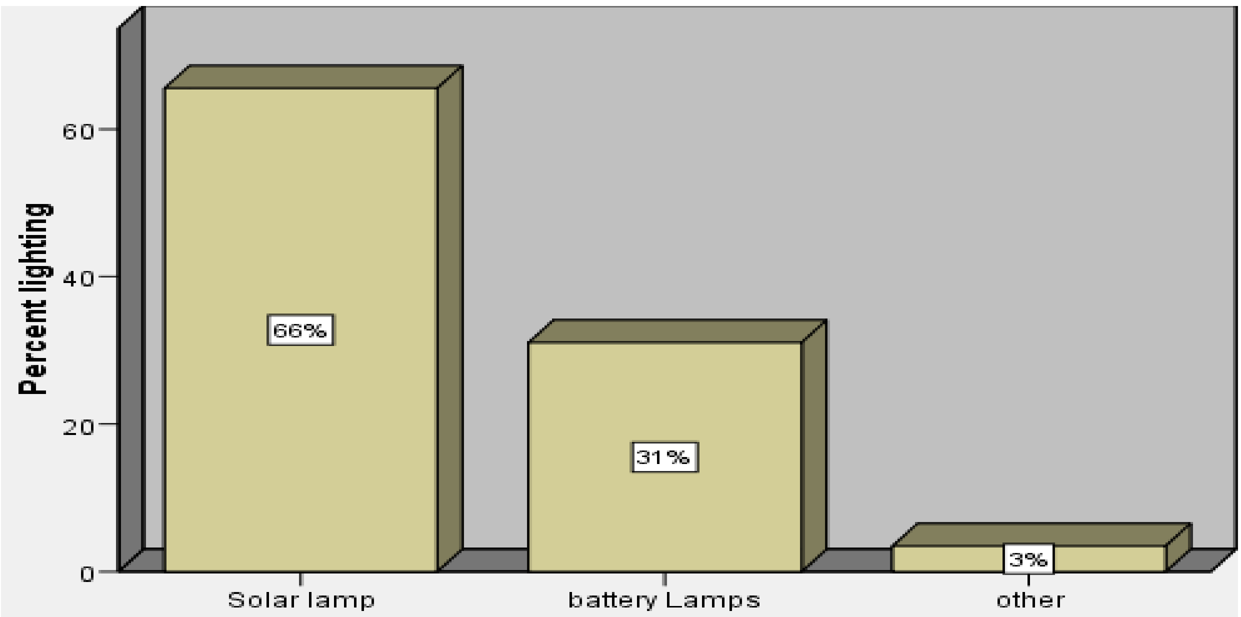

Figure 11: Current utilised lighting sources around Kalima cooperative in Chipata.

4.3.1.4 Household ability and willingness to pay for solar power

It was established that monthly, 100 % of households were willing to pay according to their ability for productive use of energy in the village. 69 % of the households were willing to make a monthly payment of ZMW50.00 and 31 % on ZMW100.00 for the solar borehole. The above narration shows approximately 10 % of their monthly income of ZMW141.00. Therefore, it would be correct to state that households would be able to pay roughly around this amount monthly for solar power.

4.3.2 Chamatete cooperative, Lumezi

Location: The village is located along Lundazi Road, approximately 74 km from Chipata town.
Latitude: 13.05687249 **Longitude:** 32.96108522

4.3.2.1 Demographics

A total of 18 households were interviewed, representing 72 % of the targeted population within a 500 m radius. The average household size was found to be seven persons. Concerning marital status, 100 % of the respondents were married. Regarding education levels, 40 % of respondents had gone up to primary school level, 50 % attained secondary education, and 10 % had no educational background.

4.3.2.2 Source of income

The survey established that most people in this area depended on farming as their source of income. Amongst them, 95 % of households reported earning most of their income from farming, while 6 % of households obtained their income from business in cooperation with farming. The estimated average annual income was ZMW20,000.00.

4.3.2.3 Current Utilised Energy Sources

To meet their energy needs, many homes use multiple sources of energy. The reviewed results after the survey for cooking/heating show that 67 % used firewood and 33 % used charcoal, while for lighting, the survey shows that 72 % used solar lamps and 28 % used battery lamps. Figures 12 and 13 illustrate the above analysis.

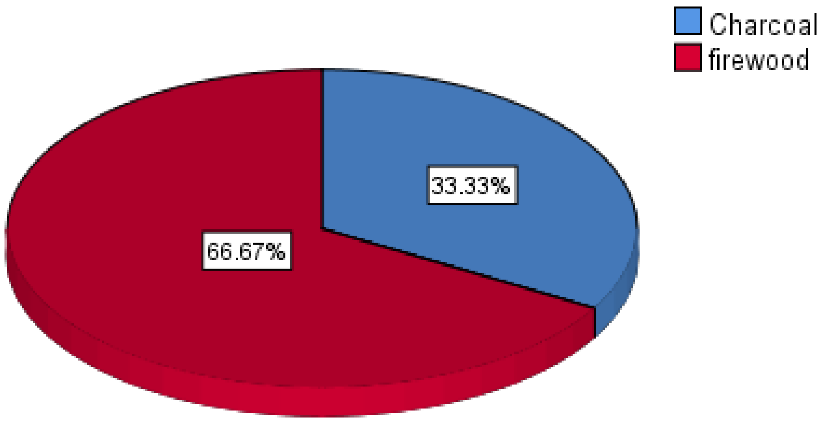

Figure 12: Currently utilised heating and cooking energy sources around Chamatete cooperative in Lumezi district.

4.3.2.4 Source of water

The survey reveals three different types of water sources in this area. 6 % of the households used to draw water from the river,72 % used to draw water from a hand pump borehole, 6 % used to draw water from a well, and 17 % of the households used both a river and borehole.

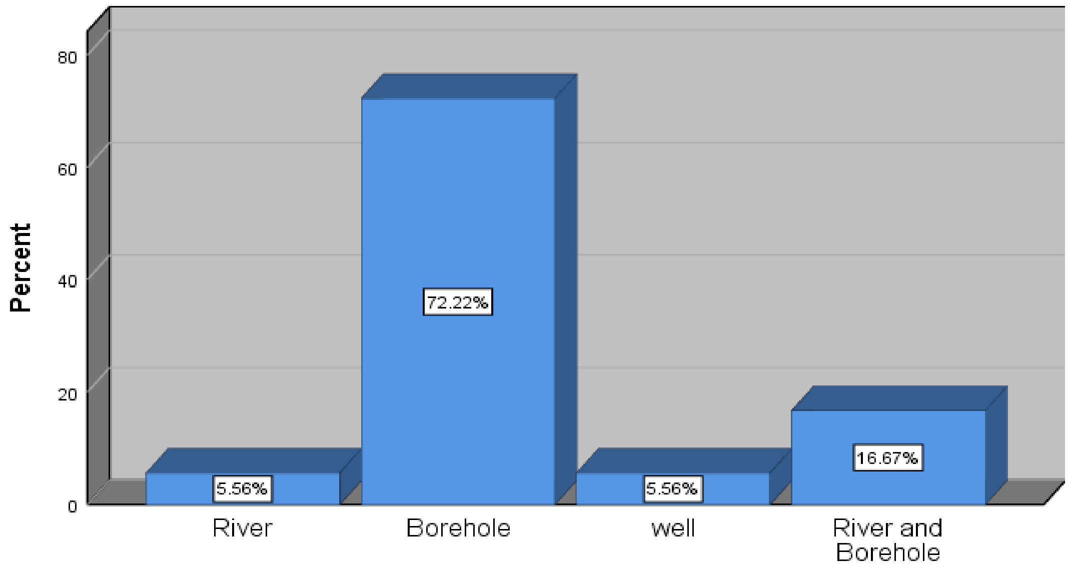

Figure 13: Various sources of water around Chamatete cooperative in Lumezi district.

4.3.2.5 Household ability and willingness to pay for solar power

All the households interviewed were willing to make a monthly payment for any productive use of energy in the village. Among them, 50 % of the households were willing to make a payment of ZMW50.00, 33 % a ZMW100.00 and 17 % a ZMW200.00 for the solar borehole once a month. On average these payments are within the range of 10 % of their monthly income (ZMW167.00). This means that many homes would pay approximately this amount per month.

4.3.3 Nkhanyu cooperative, Chipangali

Location: The village is along a tarred road approximately 64 km from Chipata town.

Latitude: -13.15650273 **Longitude:** 32.96007469

4.3.3.1 Demographics

26 households were interviewed in total and this signified 100 % of the population in target within a 500 m radius. The average household size was found to be 8 persons. About marital status, 96 % of the respondents were married, and 4 % were single. Concerning education levels, 58 % of respondents had reached primary school level, while 42 % had gone up to secondary education.

4.3.3.2 Source of income

The income generation for many households was from farming. Among the households interviewed, 89 % reported earning most of their income from farming, while 12 % received income from farming and businesses. On average, the projected income was K19,000.00 per annum.

4.3.3.3 Current Utilised Energy Sources

The study established that households used different energy sources to meet their energy needs. The survey results for cooking/heating showed that 70 % used firewood, 27 % used charcoal, and 4 % used firewood and charcoal at the same time. Analysis of energy as the source of lighting shows that 80 % used solar lamps, 20 % used battery lamps, and 4 % used other energy sources. Figure 14 and 15 gives an outline of the utilised energy sources and the current utilised lighting sources for the interviewed respondents, respectively.

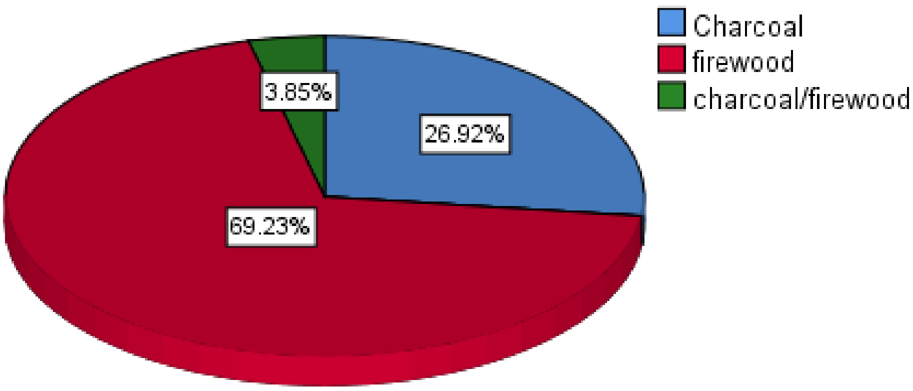

Figure 14: Current heating and cooking energy sources around Nkhanyu cooperative in Chipangali District.

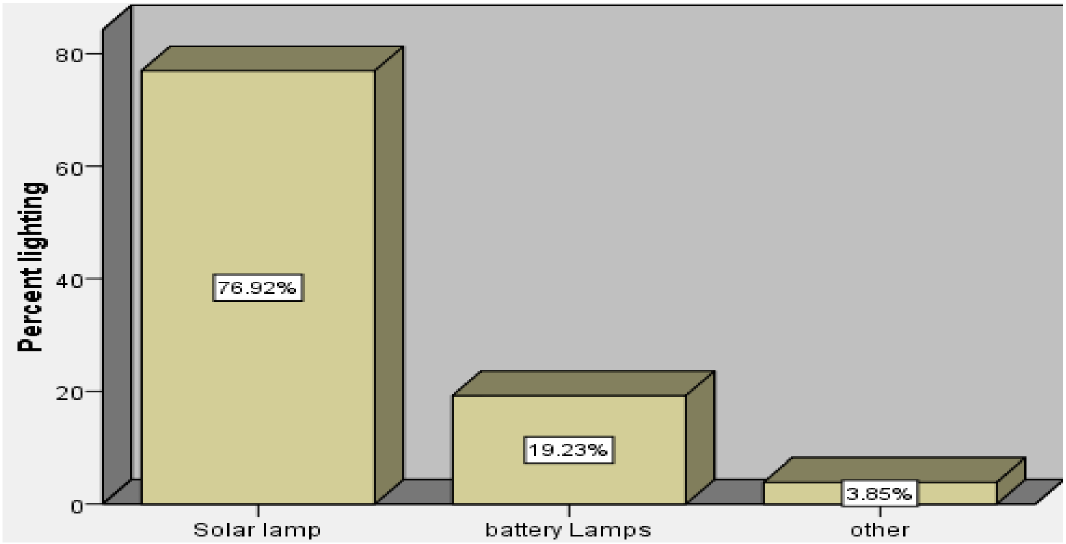

Figure 15: Current utilised lighting sources around Nkhanyu cooperative in Chipangali District.

4.3.3.4 Household ability and willingness to pay for solar power

It was established that all the households in this village depended on the hand pump borehole. It is also shown by the survey that 100 % of households were willing to pay for productive use of energy creativities in the community. 58 % of the households were willing to make a monthly payment of ZMW50.00, 31 % a ZMW100.00 and 12 % a ZMW200.00 for the solar borehole, which shows approximately 10 % of their monthly average income of ZMW157.00.

This entails that households would be able to pay roughly around this monthly on solar-powered initiatives.

4.3.4 Chiwazi Cooperative, Petauke

Location: The village is located along the road nearly 18 km from Petauke town.

Latitude: 14.35182089 **Longitude:** 31.19640727

4.3.4.1 Demographics

A total of 30 households were interviewed, representing 100 % of the targeted population within a 500 m radius. The average household size was found to be 6 persons. Concerning marital status, 100 % of the respondents were married. Regarding education levels, 50 % of respondents had gone up to primary school level, 40 % reached secondary education, and 10 % of the people had not been to school.

4.3.4.2 Household survey

The household survey helped to determine the sources of income for respondents and it was established that most people in the area depended on farming. Among the households interviewed, 70 % reported that they earned most of their income from farming, 20 % received income from Carpentry, and 10 % earned income from both farming and Carpentry. The total amount of ZMW19,000.00 was their average annual income.

4.3.4.3 Current Utilised Energy Sources

The study reviewed that households used various energy sources to cater to their energy needs. Results of the survey for cooking/heating show that 65 % used firewood, 25 % used charcoal, and 10 % used both firewood and charcoal, while for lighting shows that 80 % used solar lamps and 20 % used battery lamps. Figures 16 and 17 give a summary of their various energy sources.

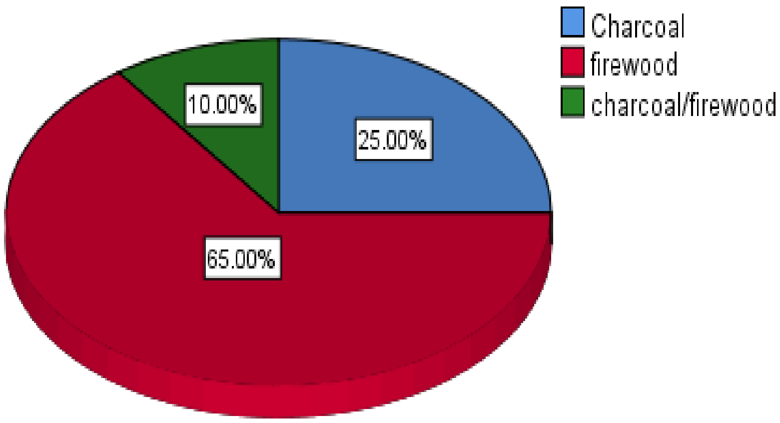

Figure 16: Shows the pie Chart of current heating and cooking utilised energy sources around the Chiwazi cooperative in petauke district.

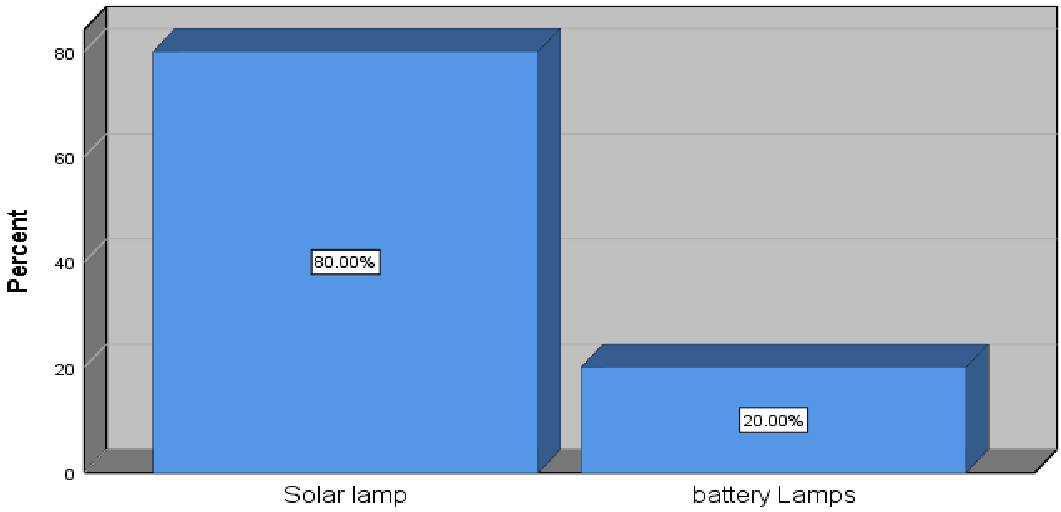

Figure 17: Shows the bar chart of current lighting sources around Chiwazi cooperative in Petauke district.

4.3.4.4 Household ability and willingness to pay for solar power

It was established that monthly, 100 % of households were willing to pay for any productive use of energy in the village.50 % of the households were willing to make a monthly payment of ZMW50.00, 40 % payment of ZMW100.00, 5 % payments of ZMW150.00, and another 5 % payment of ZMW200.00 for the solar borehole. This is roughly 10 % (ZMW154.00) of their monthly average income and it would mean they are able to pay this amount every month on solar-powered initiatives.

4.3.5 Chisongo Cooperative, Petauke

Location: This village is along the gravel road, 13 km from Petauke town.

Latitude: 14.14279126 **Longitude:** 31.38105121

4.3.5.1 Demographics

An overall of 30 households was interviewed which represented 100 % of the targeted population inside a 500 m radius. The average household size was found to be 7 persons. About marital status, 93 % of the respondents were married, and 7 % were not married. The education levels were that 57 % of respondents had gone up to primary school level, 42 % attained secondary education, and 1 % had no record of education.

4.3.5.2 Source of income

The sources of income as established by the household survey were that most people depended on farming. Out of the total households interviewed, 90 % reported that they earned most of their income from farming, while 10 % of the respondents earned their income from farming and business. Per year, ZMW18,000.00 was an estimated income.

4.3.5.3 Current Utilised Energy Sources

After the study, it was established that many households used different energy sources to meet their daily energy requirements. The results of the survey also outline the usage of energy for cooking/heating, of which 60 % used firewood, 37 % used charcoal, and 3 % used both firewood and charcoal, while for lighting it was established that 80 % used solar lamps, 17 % used battery lamps, and 3 % used other sources. Figures 18 and 19 give an overview of the utilized energy sources and current lighting sources for the interviewed respondents.

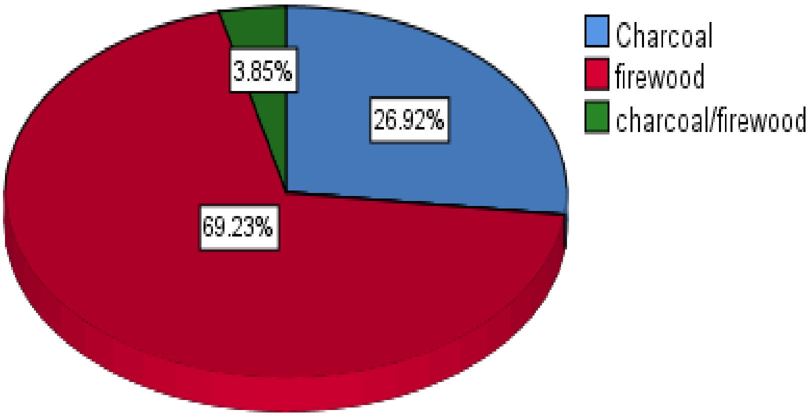

Figure 18: Current heating and cooking utilised energy sources around Chisongo cooperative in Petauke district.

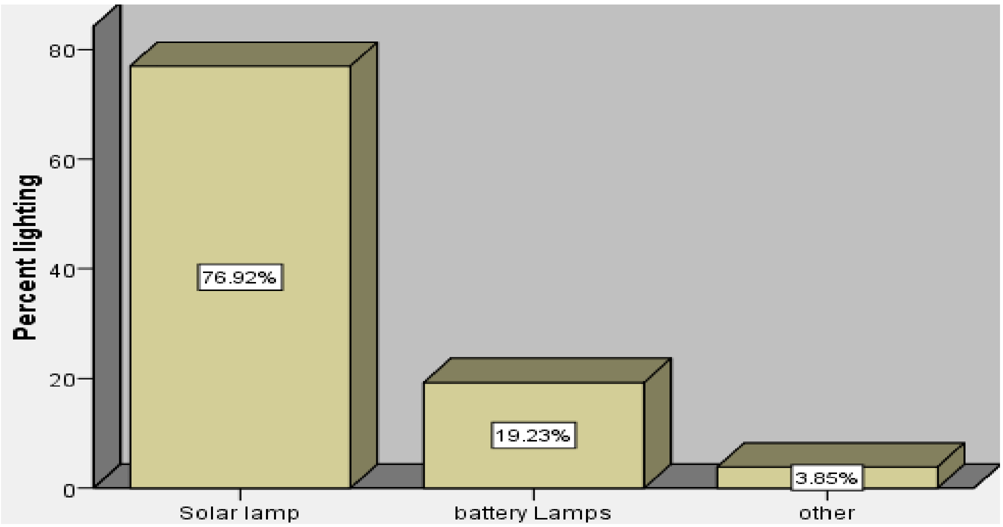

Figure 19: Current lighting sources *around Chisongo cooperative in Petauke district.*

4.3.5.4 Household ability and willingness to pay for solar power

It was established by the study that all of the households showed their willingness to pay for any productive use of energy in the village.53 % of the households were willing to make a monthly payment of ZMW50.00, 37 % payment of ZMW100.00, and 10 % payment of ZMW200.00 for the solar borehole. This is about 10 % (ZMW150.00) of their income per month on average and it can be interpreted that most households would manage to pay for solar-powered initiatives.

4.4 Technical Solution

Utilising excess solar energy efficiently is crucial for maximizing the benefits of solar power and minimizing waste. The choice of the most suitable technical solution depends on factors such as the location, energy needs, and available resources. A combination of these solutions may be used to ensure the efficient utilization of excess solar energy. Therefore, this section will discuss recommended technical solutions for the use of excess solar energy from SMPs.

4.4.1 Operational challenges of SMPs

According to section 4.2, the excess energy averages 8.5 kW (the lowest average value among the six sites according to Table 3). And this could be used by the surrounding community and the micro, small and medium-sized enterprises (MSMEs). Additionally, this is going to cause business sustainability as most of the SMPs are unsustainable due to some of the following noted reasons: - The SMP project financing was a flexible loan to the cooperative with a monthly loan repayment of ZMW1,700.00 to commence three years after the commercial operation date (COD). With the monthly loan repayment beginning in 2019, the cooperative made losses owing to a monthly revenue stream of less than ZMW1,000.00 from most cooperatives, which could not cover the debt repayment and the associated operational expenditure, which are not part of the ZMW1,700.00. These losses could be attributed to a bad harvest due to experienced drought in the previous seasons and an unsustainable business model owing to unused excess power. Another reason is that people prefer to mill their grain from an electric or fuel hammer mill to the SHM because it is cheaper and they exchange with maize bran as a form of payment in most cases and also supplies intermittency which is less or not common in electric and fuel hammer mills.

The supply intermittency is due to the SMP not having a battery bank in the system. Thus, any cloud cover leads to a stoppage of the milling plant, which challenges the cooperative to ensure sustainability. Consequently, there would be limited operating hours during the cloudy seasons and night-time, which entails that during such times, no activity occurs as the mills are propelled by the sun. Connecting the battery bank to support grinding even at night is necessary. Other challenges result from the delayed response from ZCF to conduct repairs for significant breakdowns and the supply of replacement parts. Limited availability of primary spares in the country leads to prolonged downtimes and limited numbers of customers that the mill can take in the day, even on a good sunny day, which leads to low-income levels realized by the cooperatives. The above information is explained in summary by the flow chart in Figure 20.

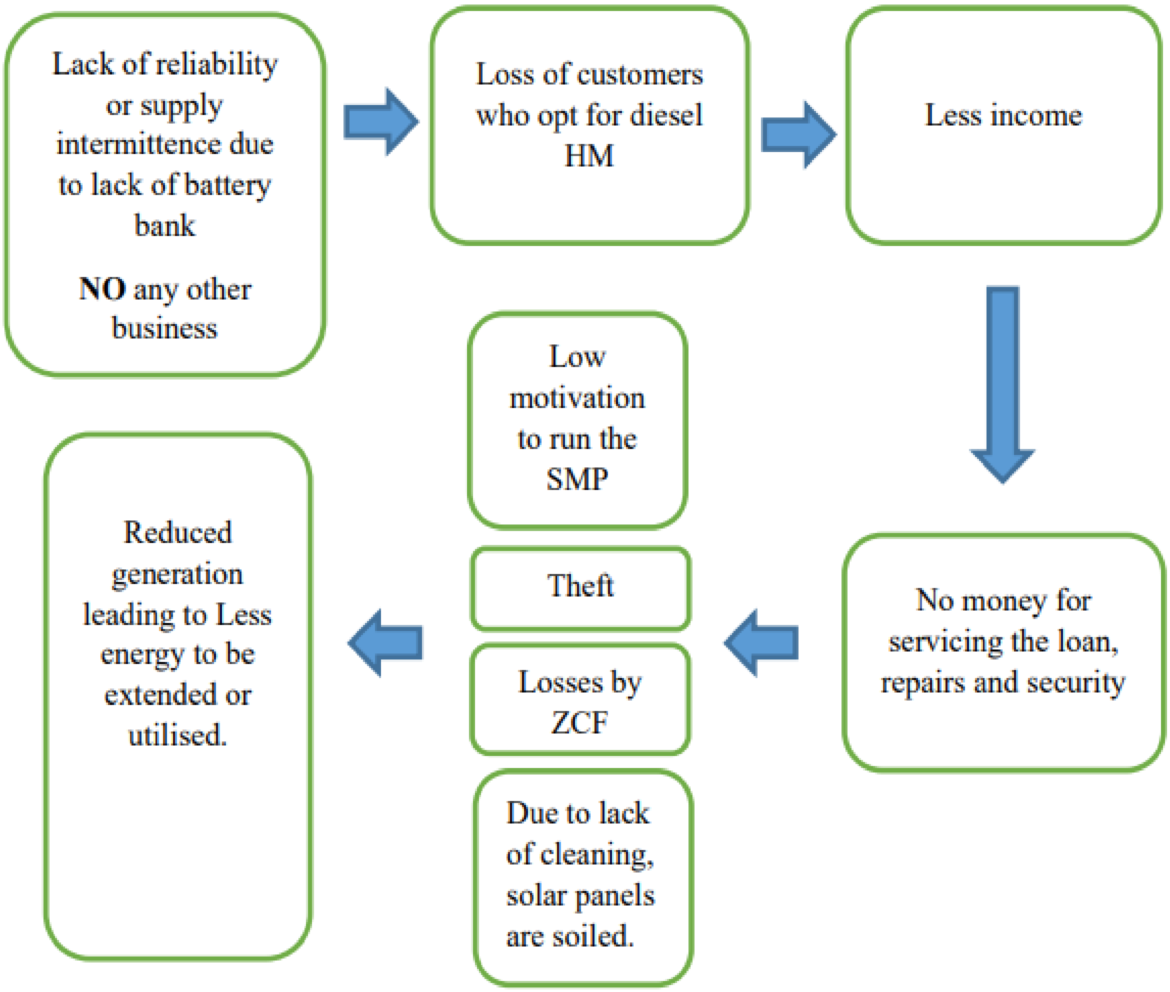

Figure 20: The flow chart showing the operational challenges of SMPs

4.4.2 Proposed solution

The proposed solution is providing a water pumping system, as most SMPs are along the roadside, which makes the optimization of the plant with business activities, possible irrigation and water management system feasible due to the presence of farming activities in the areas. Moreover, all the visited villages have at least one communal manual hand pump borehole, which has excellent potential to be turned into a solar water pumping system.

Another solution could be setting up businesses around the SMP to promote productive uses of electricity that could benefit the communities. Establishing a business hub powered by renewable energy in rural areas can offer numerous economic and social benefits, contributing to local development and sustainability. Renewable energy sources can provide a reliable and consistent power supply, enabling the growth of businesses and promoting job creation. Deploying renewable energy systems in rural areas can enhance energy security and stimulate economic growth by attracting investment and supporting entrepreneurship.

This Business hub provides an alternative approach to providing power to off-grid rural communities as the concept of an 'energy centre,' which combines elements from different systems [10]. In this setup, there is centralized power generation, but instead of distributing electricity, people pay to access services such as renting solar lanterns for home use or charging their mobile phones at a central energy centre.

Under a business hub, a solar charging station can be set up as an energy kiosk but make use of the SMP's excess solar energy for charging stations for lamps and batteries. The customers could be charged by renting out recharged batteries and lamps or simply charging for each battery/lamp charged. A single system for charging 25 batteries concurrently and commercially charging up to 25 solar lamps.

4.4.3 Proposed SMP Configuration

Figure 21 illustrates the general proposed structure that should be implemented by splitting the existing configuration of SMP into two, one dedicated to Carter for the milling demand and the other for additional demand due to the integration of a solar water pumping system and a business hub.

Figure 21: Proposed SMPs energy utilisation

4.4.4 Solar System Sizing

System sizing starts with assessing the existing milling demand for the split system shown in Figure 21 and ends with the required solar photovoltaic and battery capacity to meet the energy demands. SMPs have maximum working power and excess unutilized, as detailed in section 4.1. Sizing incorporates community energy needs (as highlighted in section 4.3), which plays a vital role in the sizing of the system because it helps in comparing the energy demand of the community to the available energy (excess energy in this case). Table 4 illustrates solar system sizing for a business hub.

4.4.5 Solar sizing for a business hub

Table 4: Estimation of the peak watt and daily energy consumption for a business hub

Appliance	**Quantity** **A**	**Wattage (W)** **B**	**Hours of Use** **C**	**Total Wattage (W)** **A x B = D**	**Energy Demand (Wh)** **C x D**
Business					
Grocery shops (6)					
Lighting bulbs	6	5	4	30	120
EE Deep Freezers	6	20.6	12	123.6	1483.2
Barbershops (2)					
Lighting bulbs	2	5	4	10	40
Clipper/shaver machine	4	11	6	44	264
Bars (2)					
Lighting bulbs	2	5	4	10	40
Stereo	2	60	5	120	600
EE Deep Freezers	2	20.6	12	41.2	494.4
Dstv Decoders	2	25	6	50	300
Internet café (1)					
Computer	5	90	6	450	2,700
Photocopying/printer	1	15	6	15	900
Phone charging	15	5	4	75	300
Wi-Fi router	1	30	6	30	180
Fan	1	40	2	40	80
Charging station					
Home battery charging	25	30	4	750	3000
Solar lamps	25	10	4	250	1000
Other					
Water pump (1)	1	1,500	8	1,500	12,000
Security lights (11)	11	5	12	55	660
				3,593.8	**24,161.6**

The following assumptions emanating from the energy consumption as shown in Table 4 were made: -

i. For *Grocery shops*, a total of 6 grocery shops with each shop owning a deep freezer, one room and will have one light bulb.
ii. For *Barbershops*, a total of 2 barber shops have two shaving machines and a light bulb.
iii. For *Bars*, a total of two bars. A bar has one room with an outdoor toilet with a light. Both bars own stereo for entertainment and an energy-efficient fridge.
iv. For *Internet café*, one Internet café to service the entire village and surrounding communities. Furthermore, it will have five computers, one Wi-Fi router, one photocopier/printer, one fan, and 15 fee-paying phone charging points.
v. For a *charging station*, a single system for charging 25 batteries concurrently, with each battery having 200 Ah, 24 V and charging 25 solar lamps, with 10 W capacity each.
vi. Lastly, *for the solar water pump*, one solar water pump will be used for clean water provision to all the residents in the surrounding community and supplying water to a fish pond, poultry, and farming, i.e., growing vegetables.

4.4.6 Solar PV sizing calculations

- PV Array Wh

24,161.6 Wh + (25 % of 20,161.6 Wh) = 30,202 Wh (accounting for the losses)

- PV Array Size

$$\frac{total\ energy\ demand(Wh)}{average\ sun\ hours} = PV\ array\ size$$

$$\frac{30{,}202\text{Wh}}{4\text{ hrs}} = 7{,}550.5\text{ W} \sim 7.55\text{ kW}$$

- Required battery bank

Appliances use 30,202 Watt-hours/day, nominal battery voltage = 2 volts, days of autonomy will be 2 days and efficiency = 85 %, Depth of discharge = 0.5 and system voltage = 24 volts

$$\frac{total\ energy\ demands \text{ x } days\ of\ autonomy}{efficiency \text{ x } depth\ of\ discharge \text{ x } system\ voltage} = battery\ bank\ capacity$$

$$\frac{30{,}202 \text{ x } 2}{0.85 \text{ x } 0.5 \text{ x } 24} = 5{,}921.960784\text{ Ah}$$

The total battery bank capacity required is approximately 5900 Ah.

-Choosing a 2 V 2,300 Ah battery

$$Number\ of\ batteries\ in\ series = \frac{system\ voltage\ (V)}{One\ cell\ voltage\ (V)}$$

$$\frac{24\ V}{2\ V} = 12\text{ batteries in series}$$

$$Number\ of\ batteries\ in\ parallel = \frac{battery\ bank\ capacity\ (Ah)}{battery\ capacity\ (Ah)}$$

$$\frac{5900Ah}{2300\ Ah} = 2.565217391\ \sim 3\text{ parallel connections}$$

4.4.7 Solar water pump sizing

- **Water demand requirement**

In rural Zambia, a person needs approximately 40 litres of water daily [56].

Bathing = 15 litres

Drinking = 5 litres

Washing + cooking/cleaning = 15 litres

Other uses = 5 litres

- Number of people
  [Number of houses ranges from 25 to 30]

  8 persons (average per household) x 30 houses = 240 people

- Total water demand

40 litres x 240 people = 9,600 litres of water ∼10,000 L/day

- Chicken Poultry Water Demand
  [Assumptions made: 3,000 broiler chickens need approximately 4,000 litres of water per day and 1,000 Chickens other than broilers would need 605 litres of water. This amounts to approximately 5,000 litres of water in total per day] [57].
- Irrigation water demand
  [Assumptions made: Approximately 1,500 square metres of land would need around 15,000 litres of water per day for irrigation of vegetables and most grain crops] [58].

  Water demand for irrigation = 15,000 L/day

  Poultry water demand approximation = 5,000 L/day

- Total water demand

  Home consumption + Irrigation + poultry ∼ 30,000 L/day

The total water demand for the system equates to 30,000 L/day**.** Therefore, this amount of water must be provided within the pump hours (6 hours), from 09 hrs to 15 hrs.

4.4.7.1 Pump description

choosing a 1.5 kW 2 hp pump

- Specification

-Voltage: 220-240 V/60 Hz

-Motor: 2 HP / 1.5 kW, single phase

-Max-flow: 158 L/min = 9,500 L/hr

-Max head: 134 m

-In 1 hr 36 minutes, this pump would fill up 15,000 litres of water.

9,500 L/hr x 1.6 hrs = 15,000 L

Therefore, to meet the 30,000 litres demand, another 1 hr 36 min would provide an additional 15,000 litres.

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This research aimed to study the performance of SMPs and propose the possible extension of excess energy from solar milling plants to productive uses in surrounding communities. The objectives of this study were to conduct a sample survey to assess the technical configuration and performance of the three generations of the SHMs, assess average daily energy generated, energy consumed and excess unutilised energy of selected SMPs, to conduct energy needs assessments for the surrounding rural communities and finally, to recommend a design of an effective technical solution to ensure productive use of excess solar energy from SMPs.

In order to achieve these objectives, a technical investigation was done to obtain technical data, operations of six SMPs and the energy needs assessment of the surrounding communities. REA and ZCF officers also provided the operational study data and preliminary information. Finally, a concept design for a solar water pumping system and a business hub around the SMP was recommended to benefit the local communities.

The analysis of the measured and observed data on SMPs configuration and performance shows a comparative difference, with each generation having positive and negative attributes. Therefore, combining the positive features would produce an improved SHM generation. The second and third generations have the advantage of using less minimum power to operate. They are automated, making them easy to use even when there is low solar power and less technical knowledge is required for local operators. The analysis of average daily energy generated, energy consumed, and excess unutilised energy of selected SMPs varies from one SMP to another depending on the installed capacity and how often or regularly local operators clean the solar panels. The analysis showed that the second and third generations of SHMs were lower power-rated and were technically friendly to the local operators. The first generation utilises approximately 50 % of the energy generated, and about 30 % of the generated energy for the second and third generations is utilised. The analysis of energy needs assessments for the surrounding rural communities was summarised in the household survey results in the form of demographics, housing characteristics, household sources of income, household energy sources and the household willingness and ability to pay for electricity.

On average, 40 % to 58 % of the population around the SMP had primary education, which is the lowest level of education in Zambia. This could have a negative effect on the management and development of SMP. And this could be one of the reasons why the SMPs project seemed not to be properly managed. The average number of houses within a 500 m radius ranges from 25 to 30, with an average number of rooms ranging from five to eight. Targeting households within this radius helps ensure that energy access is acquired equitably. It prevents a concentration of energy benefits in one area while leaving others underserved, promoting social and energy equity within the community. Furthermore, the community's economic activities were farming and various businesses (such as beer selling and grocery), with an average annual income going from ZMW16,000.00 to ZMW20,000.00. Business-minded co-operators could utilise the SMP as a business. Again, 67 % average source of energy for cooking is from firewood, and 74 % is the average energy source from solar lamps for all the visited sites. This shows that most residents in these rural areas are already experiencing and appreciating the idea of solar technology. It was also established after analysis that monthly; 100 % of households were willing to pay a minimum of ZMW100.00 per month for solar energy initiatives because it is considered to be reasonably less than 10 % of their monthly income on average (the 10 % range per month is from ZMW130.00 to ZMW167.00).

Finally, a 15 kW hybrid inverter was recommended to connect a solar water pump and a business hub around the SMP. This class of inverter can handle high voltages from the SMP solar array. A 1.5 kW solar water pump was selected to manage the total water demand of 30,000 L/day. Regarding business, a minimum of 7.6 kW is required to meet the demand for shops, security lighting and a portable battery charging station. A 5,900 Ah battery bank is required to supply power to the system to meet power downtimes.

5.2 Recommendations

The study recommends the following:

1. To increase the safety of SMPs, ZCF should work hand in hand with the local communities to intensify security systems and reduce theft chances,

2. To ensure continued proper functioning as a business for SMPs, local community leaders should sensitize the people on the benefits of milling their grain from their local SMP to support development. Of course, at a cost of good service provision.

3. Promote a deliberate cleaning program for solar panels to appreciate the full maximum production of solar energy.

4. There is a need for increased access to the maintenance regime by the operators otherwise when the maintenance period (service contract under the equipment supplier) elapses it may be difficult to keep the equipment in operation.

5. Development of business models for the activities suggested in this study.

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APPENDICES

Appendix 1: Household Questionnaire

THE UNIVERSITY OF ZAMBIA SCHOOL OF NATURAL SCIENCES
DEPARTMENT OF PHYSICS

QUESTIONNAIRE No:

MASTER OF SCIENCE IN PHYSICS

EXTENDING ENERGY USAGE OF SOLAR MILLING PLANTS INITIATIVE IN ZAMBIA

NEEDS ASSESSMENT OF THE COMMUNITY AT THE HOUSEHOLD LEVEL

General information / Bio Data

Marital status: …………………………………………

The number of family members: …………………………..

Name of the village: …………………………………..

Education

Primary education ☐

Secondary education ☐

Tertiary education ☐

Other, specify……………………..

Building structure

How many rooms does your house have?

1 ☐ 4 ☐ 7 ☐

2 ☐ 5 ☐ 8 ☐

3 ☐ 6 ☐ 9 Other, specify…….

Type of roof

Grass thatched ☐

Iron sheets ☐

Asbestos ☐

Other, specify……………..

Household needs

What appliance would you like to own when power is available?

Tick where applicable

Appliance	Number of appliances
TV ☐	☐
Stereo ☐	☐

Fun ☐ ☐

Decoder ☐ ☐

Lighting ☐ ☐

Laptop ☐ ☐

Phone Charging ☐ ☐

Refrigeration ☐ ☐

Computer ☐ ☐

Energy usage

What do you use for heating/cooking?

Biomass ☐

Charcoal ☐

Other, Specify………….

What do you use for lighting?

Paraffin Lamp ☐

Candle ☐

Solar Lamp ☐

Battery Lamps ☐

Other, Specify…………

What is the source of water?

River ☐

Borehole ☐

Well ☐

Other, Specify…………

If you got your water from the borehole, are you willing to pay for the service if it's run by solar?

YES ☐ NO ☐

Income

What do you do for a living/what is your occupation?

Farmer ☐ Barber Man ☐ Civil Servant ☐

Fisherman ☐ Businessman ☐ Other, Specify………………

What is your monthly income?........................

What is annual income?...................................

Willingness to pay and Affordability

Are you willing to pay for electricity if provided?

YES ☐ NO ☐

How much can you afford?

K50 ☐ k100 ☐ k150 ☐ k200 ☐ Other, specify………

Appendix 2: Technical information from SHMs operators, ZCF, REA questionnaire

THE UNIVERSITY OF ZAMBIA SCHOOL OF NATURAL SCIENCES
DEPARTMENT OF PHYSICS

QUESTIONNAIRE No:

MASTER OF SCIENCE IN PHYSICS

EXTENDING ENERGY USAGE OF SOLAR MILLING PLANTS INITIATIVE IN ZAMBIA

QUESTIONNAIRE
This is a survey questionnaire aimed at getting information and documentation from Solar Hammer Mills Operators, ZCF officers, REA officers and other partners on the extending energy usage of solar milling plants initiative in Zambia. The information received will be treated with the confidentiality it deserves, as this is purely an academic exercise.
SECTION 1: INTERVIEWEE BIO DATA Gender…………………………………………… Occupation…………………………………… Cell Phone Number……………………………… Residential Address……………………………..
SECTION 2: EDUCATION Tick where applicable; University ☐ College ☐ Secondary School ☐ Primary School ☐

SECTION 3: SHM PLANT CONFIGURATION

1. What is the number of solar panels available on the plant………………………………
2. Which type/cell technology of solar modules is installed? Tick where applicable

Monocrystalline ⬭

Polycrystalline ⬭

Amorphous ⬭

Cadmium (Cd-Te) Tellurium ⬭

3. How many solar modules are in one string? ……………………………………………..
4. How many are connected in parallel? ……………………………………………
5. What is the rated peak power of one solar module? …………………………………………………………………………….
6. What is the string voltage (V)? ………………………………………………………………………………
7. Do the solar modules have a warranty? ⬭ Yes ⬭ No
8. What is the inclination angle?...
9. Which direction are the solar modules facing; tick where applicable

North ⬭

East ⬭

South ⬭

West ⬭

Other, specify……………………………..

10. How many milling machines are used for the solar plant?...

11. Which type/types are they; Tick where applicable

First-generation

Second generation

Third generation

12. What is the capacity/wattage of the first generation SHM?...

13. What is the capacity/wattage of the second generation SHM?.......................................

14. What is the capacity/wattage of the third generation SHM?...

15. When was it commissioned or started operation? …………………………………….

16. How has it been performing since inception?...
....