Technical and Economic Performance Assessment of Solar Milling Plants in Zambia

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Abstract:- In 2015, the Zambian government embarked on a proactive endeavor to enhance the accessibility of economical maize meal through the inception of the Solar Powered Milling Plants (SMPs) Project. The Chinese Government and the Government of the Republic of Zambia jointly provided co-financing, supporting this audacious initiative with a significant financial commitment of US$200 million. However, there have been no documented results on the technical and economic performance of the solar milling plants.

To this effect, this study aimed to establish the technical and economic performance of the milling plants installed by the Zambia Cooperative Federation. To achieve this, the study sought to: (1) establish the technical operational characteristics of the installed SMPS; (2) establish the factors that influenced the sitting of the plants; (3) determine the economic benefits of the SMPs; and (4) benchmark the technical operating conditions of the installed SMPs. The study employed a mixed methods approach, where benchmarking observations and semi-structured questionnaires were used as data collection instruments. The sample size of the study was 168, comprising cooperative leaders, solar milling plant operators, and community members from the 12 sites in Masaiti, Chikankata, Solwezi, and Kapiri Mposhi districts where the milling plants were installed.

The field observations and questionnaires that were used for the study showed that all twelve sites in the Solwezi, Masaiti, Kapiri Mposhi, and Chikankata Districts needed the same amount of power to run, which was between 7.5 kW and 9.0 kW. However, only Site 3 in Solwezi and Sites 4 and 5 in Masaiti Districts strictly followed the standard operation time of 8 hours.

The study has also shown that the two main factors that influenced the placement of the solar milling plants were proximity to the main roads of the communities and the availability of land near the Food Reserve Agency(FRA) shades. With regards to economic benefits, the generated results showed that the installed milling plants brought about employment creation as two operators were employed for each of the 12 sites. However, the revenues generated by the solar milling plants were not economically viable for loan repayment.

The study recommended that predictive and corrective maintenance, in addition to project management training for cooperatives and operators, be carried out to improve the technical and economic performance of the solar milling plants.

Keywords:- *Solar Power, Economic Performance, Solar Milling Plants, Project Management, Benchmarking.*

I. INTRODUCTION

Grain crops are essential for African nations' food supply, but limited energy access, rising costs, and national energy deficits hinder the provision of staple foods at affordable prices. The process of grain processing relies on diverse energy sources, including human labor, conventional fossil fuels, and hydropower. Traditional milling practices often rely on diesel engines, presenting inefficiencies, environmental hazards, and exorbitant operational costs.

The African Energy Outlook of 2021 emphasizes the urgent need for transformative measures to address these issues. Governments have turned to renewable energy alternatives, such as solar-powered maize milling facilities in Zambia, which taps into abundant solar resources and provides off-grid energy solutions. Solar milling plants, also known as solar-powered milling plants (SMPs), utilize solar energy to power grain milling machines, integrating photovoltaic (PV) solar panels with milling equipment to convert solar energy into electricity.

Globally, solar milling plants have gained popularity as a promising solution to address energy and food security challenges, particularly in regions with limited access to reliable electricity and fossil fuels. In Zambia, the Solar Powered Milling Plants (SMPs) Project has promoted the adoption of solar milling plants, aiming to provide low-cost maize meal and generate employment opportunities. Around 1600 solar milling units have been successfully installed since its launch.

By harnessing solar energy for food processing, Zambia exemplifies a sustainable approach to energy utilization, paving the way for positive socioeconomic impacts. This initiative not only benefits local communities by providing affordable maize meal but also fosters environmental stewardship by reducing reliance on fossil fuels.

As the global shift towards clean and sustainable practices continues, there is a growing emphasis on exploring renewable energy sources like solar photovoltaic (PV). Zambia, like many other countries, has made

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24APR2202

significant progress in adopting PV-powered off-grid solutions for both domestic and commercial applications.

- *Maize Consumption in Zambia*

Maize is a significant staple crop in both eastern and southern Africa, covering 23% of the primary cropping area and contributing to 22% and 21% of the calorie supply and 30% and 27% of the protein supply respectively. Its cultivation and management are characterized by distinct seasonal patterns, with the major harvest occurring predominantly over a concentrated two-month span. In Zambia, the annual maize consumption is 2.8 million metric tons, serving various purposes such as meeting the dietary needs of the population, providing fodder for livestock, and contributing to industrial processes.

Maize consumption in Zambia varies significantly, with individuals consuming anywhere from 52 to 243 grams per person per day. This high level of consumption highlights the cultural and nutritional significance of maize in Zambia, as well as its economic relevance. The dietary habits of Zambia provide insights into the profound connection between people and maize, highlighting its broader impact on the cultural identity and economic dynamics of the nation.

Solar milling plants are particularly viable in tropical countries where solar radiation is abundant and consistent throughout the year. By harnessing solar electricity, these plants can contribute to reducing reliance on traditional fossil fuels for powering industrial processes, thereby lowering carbon emissions and promoting environmental sustainability. Solar milling plants typically consist of three key components: a solar panel station housing solar modules that generate the necessary energy to power the milling machine, an inverter that converts DC electricity into AC voltage for the machine motor, and a switch to regulate the machine's operation.

In 2015, the Zambian government initiated the Solar Powered Milling Plants (SMPs) Project, supported by the Chinese Government and the Government of the Republic of Zambia, with a significant financial commitment of US$200 million. The project aimed to reduce the cost of mealie meals and promote employment for the people of Zambia. Since 2015, approximately 1600 solar milling units have been set up in Zambia.

The Zambia Cooperatives Federation (ZCF), overseeing multiple cooperatives, spearheaded the implementation of the SMP project nationwide. Primary cooperatives seeking access to the project needed to meet specific loan conditions, including paying a K500 application fee, demonstrating land availability for the mill installation, showcasing good governance practices, and committing to a monthly loan repayment of K1,700 for fifteen years upon receiving the milling plant. Additionally, they were required to sign a contract with ZCF.

- *Statement of the Problem*

The Solar Milling Plants project, funded by the Chinese and Zambian governments, aimed to create a $200 million investment. However, there is a lack of information on the technical and economic performance of these plants, leading to concerns about their effectiveness and financial sustainability. Despite media discussions about underuse, there is a lack of information on the actual performance of these setups, hindering effective decision-making. The project's effectiveness is uncertain, highlighting the need for evaluating their technical and economic aspects in solar technology planning and operation. Balancing technical and economic aspects is crucial for the development and operation of solar energy systems. The research aimed to provide insights on decision-making in installation stages, integration, and operational benefits of these plants.

- *Objective*

The main objective of this study was to establish the technical and economic performance of selected solar milling plant units installed by the Zambia Cooperative Federation in Zambia.

- *Specific Objectives*

The Specific Objectives for this research included the following.

- To establish the technical operational characteristics of the installed SMPs
- To establish the factors that influenced siting of the plants.
- To determine the economic benefits from the SMPs
- To benchmark technical operating conditions for the installed SMPs

- *Research Questions*

Below are the research questions this study sought to answer.

- What technical and economic considerations were made at inception/ project design stage?
- How is a Milling Plant daily production affected by the plant’s local site conditions?
- What variables should be considered for a SMP efficient and productive performance?
- What Economic benefits were generated for the local communities from the operation of the SMP?

- *Scope*

The study focused on 12 selected Solar Milling Plants (SMPs) across Zambia's four agro-ecological zones. Weather patterns in Zambia are associated with these zones, just as the agricultural output of maize has to some extent a relationship with the agro-ecological zoning.

- *Justification*

The lack of comprehensive data on the technical and economic benefits of solar milling plants (SMPs) highlights the need for in-depth research on their performance. This was crucial to ensure the cost-effectiveness and realization

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24APR2202

of their intended benefits. Research was essential to justify financial commitments, evaluate their contribution to social and economic growth, and assess their long-term sustainability. A detailed analysis of operational benefits was necessary to support ongoing use and potential expansion. The absence of such research would hinder the assessment of SMPs' contribution to sustainable development and livelihood enhancement in rural regions. A data-driven approach would ensure efficient resource allocation to maximize the benefits of SMPs.

II. LITERATURE REVIEW

- *Solar Energy Resource*

The sun, a sphere of intensely hot gaseous matter, serves as the primary source of solar energy for Earth. Located approximately 1.5x10^8 km away, solar energy reaches our planet in about 8 minutes and 20 seconds, traveling at the speed of light. Through thermonuclear reactions, the sun continuously converts hydrogen into helium, generating vast amounts of energy according to Einstein's equation, E=mc^2. This process has been ongoing for billions of years and is expected to continue for billions more. With a temperature of approximately 5800K, the sun emits radiation across various wavelengths, including ultraviolet, visible light, and infrared. Notably, visible light, ranging from 400 to 700 nm, is utilized by photovoltaic cells to produce electricity.

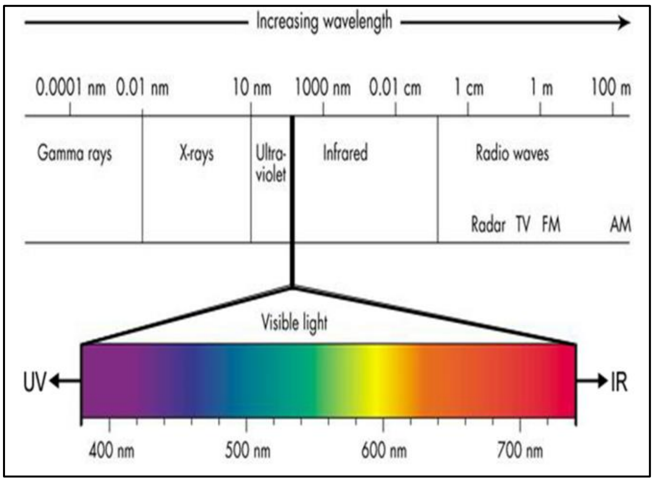

Fig 1 Visible Light Spectrum,
Source: Kaluba V-REE 6021 Handout 2020

- *Solar Energy Conversion using Solar Cells*

The working principle of solar cells is based on the photovoltaic effect, i.e., the generation of a potential difference at the junction of two different materials in response to electromagnetic radiation. The photovoltaic effect is closely related to the photoelectric effect, where electrons are emitted from a material that has absorbed light with a frequency above a material-dependent threshold frequency. These emitted electrons cause an electric field in the connected circuit, and the electricity is produced. Solar electricity depends on the PV cell's efficiency, which relies on the semiconductor materials bandgap, solar series, and mounted on support structure known as a module. The PV array is formed by connecting these modules through electric wires. Solar production depends on the size of the array.

As shown in the band diagram in figure 1, absorption of radiation can occur on both sides of the junction, creating minority carriers that can diffuse towards the junction. A photocurrent is generated if the minority carriers can drift across the junction without recombination. In practice, the p-n junction is shallow, and absorption will occur predominantly on one side where there is a greater depth of absorbing material (C. Honsberg and S. Bowden 2017).

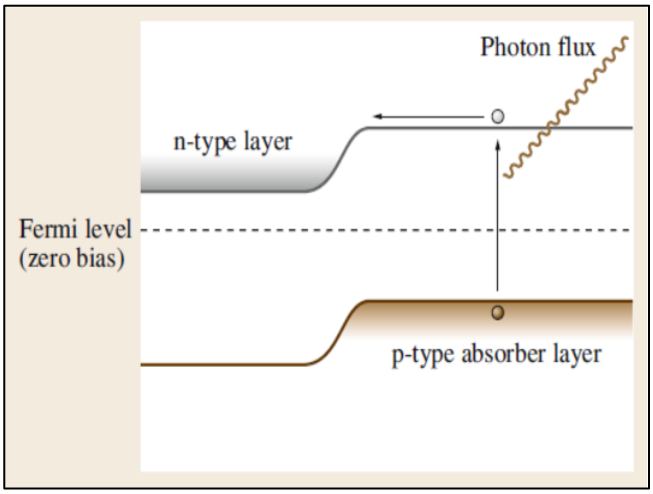

Fig 2 Schematic of Energy-Band Diagram
Source: Honsberg & Bowden, 2017)

- *Composition of a PV System*

A photovoltaic system (PV) is composed of semiconductor devices that convert sunlight to direct electricity (current DC). Photovoltaic (PV) energy technologies are becoming increasingly prominent in the global energy mix. PV is one of the fastest-growing industries worldwide (Tyagi, Nurul, Rahim, & Selvaray, 2013). These trends are thought to be closely related to vast PV cost reductions over the last years. One of the key factors is the low intensity of greenhouse gas (GHG) emissions associated with PV technologies. Contrary to fossil fuel plants, PV plant energy generation is not associated with local pollution from the release of SO2, NOx, CO, volatile organic compounds (VOCs), particulate matter (PM) or residual flue gases. These compounds have a direct adverse effect on the environment as well as on human health (Kampa & Castanas, 2008).

- *PV Electrical Model*

A PV module is a nonlinear device and can be represented by its I-V characteristic curve. There are many mathematical models which describe I-V curve. One of them is the famous five parameter photovoltaic model proposed by Duffie and Beckman (2006). The equivalent circuit for a single PV cell is shown in Figure 4. The I-V characteristic of this model is given by a well-known and extensively used Eq. (1) at a fixed temperature and solar radiation:

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24APR2202

$$I = I_L - I_o\left[\exp\left(\frac{V + IR_s}{a}\right) - 1\right] - \frac{V + IR_s}{R_{sh}}$$ ………………e.q1

Where I and V represent the current and voltage at the load condition. The circuit requires that five parameters be known, and they are, light generated current (I_L), diode reverse saturation current (I_O), series resistance (R_S), shunt resistance (R_{sh}), and ideality factor (a). The five parameters in the model are obtained using I-V characteristics of a module at reference condition supplied by the manufacturer and other known PV characteristics. PV electrical characteristics are measured under standard reference conditions, which include 1000 W/m^2 incoming radiation, a cell temperature of 25 °C, and a spectral distribution corresponding to an air mass of 1.5.

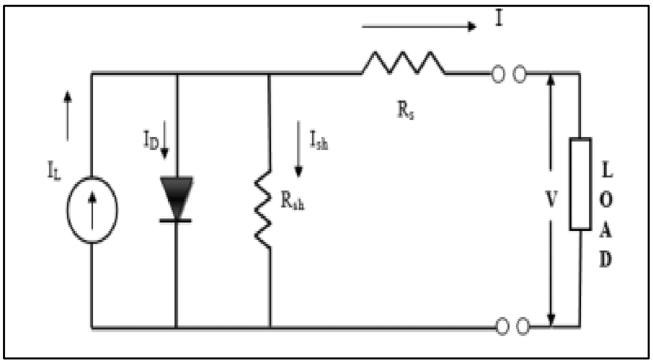

Fig 3 Equivalent Circuit of an Individual Solar Cell Source: Duffie & Beckman, 2006)

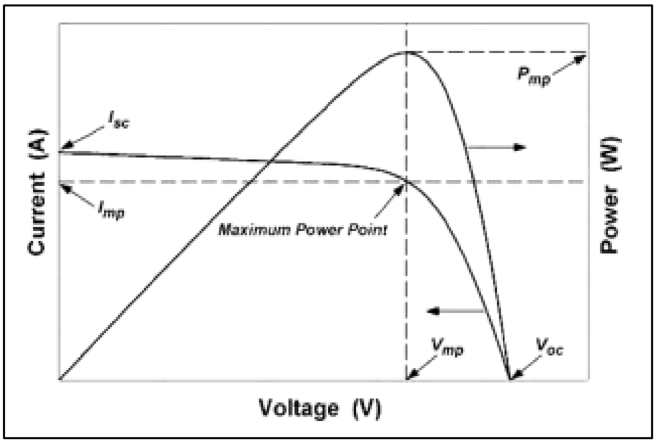

Fig 4 1-V and PV curves for PV module Source: Duffie & Beckman, 2006)

- *PV Solar Modules*

Modules are the critical elements in PV technology categorized into two main groups: crystalline silicon (c-Si) and thin-film solar cell (TFSC) based on their manufacturing technology. More than 90% of the installed PV modules are silicon-based on the material's abundance and the low processing cost. Modules based on other semiconductors such as cadmium telluride, gallium arsenide, and copper indium have a low contribution in the PV market due to their lower efficiency and higher cost. Carbon-based semiconductors are also used to manufacture solar cells, which need to improve their efficiency and lifetime. Crystalline silicon (c-Si) solar cells are manufactured from pure silicon, divided into mono-crystalline and multi-crystalline cells.

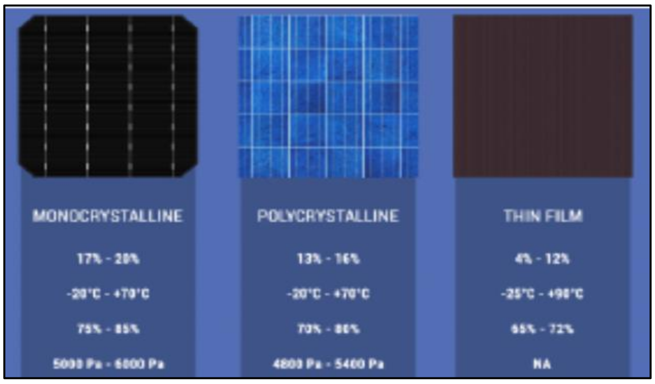

Fig 5 PV-Module Types

Mono-crystalline solar cells are made by cylindrical silicon bars. These silicon bars are cut into four sides to make silicon wafers which improve the module efficiency. At present, mono-crystalline solar panels have 17%-20% efficiency. These cells require less installation area and provide a high lifetime compared to others. Moreover, they can produce more power in low sunlight intensity. The main limitation is the high production cost with a massive wastage of raw silicon in the production process (Yinghao Chu and Peter Meisen 2011). Figure 9 presents the three PV module types. Multi-crystalline silicon (mc-Si) based solar panels are manufactured by melting raw silicon and poured into a square mold before cutting into perfectly square wafers. The advantages of these cells are low production cost and that less silicon is wasted. It has lower efficiency around (13%-16%) and required a large area in comparison with mono-crystalline.

Moreover, the cell performance is degraded with the increase of outdoor temperature. Thin-Film Solar Cells (TFSC) are made by keeping several thin layers of semiconductor materials on a substrate. The PV market share of this technology type is only 7%-10%, which is very low compared with others due mainly to their lower efficiency (7%-13%). It requires a larger area which increases the balance of system cost and panel degradation rate. The main advantage of TFSC cells is the simple production process at a low cost. Amorphous Silicon (a-Si) based solar cells have lower efficiency (6%-8%) and used for small-scale applications. Stacking technology is used to improve their efficiency and installing for large systems, which is expensive. Cadmium telluride (Cd-Te) is the most cost-efficient TFSC Compared with crystalline silicon solar panels for a more extensive system and has an efficiency of around 9%-11%.

- *Technical Aspects of a Solar Milling Plant*

Grains are the most commonly produced and consumed food crop in the Global South, and milling is critical to processing these grains for sale and consumption

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24APR2202

(Efficiency for Access, 2021). According to Culpin (1992), grinding of grains has been practiced since very early times when a device resembling a pestle and a mortar was employed in the production of meal for human consumption. Early mill houses were powered by water or animals to turn a grinding stone.

Brain and Rottger (2006) reported that in the mid-nineteenth century, electric motors were invented and higher speed machines, such as hammer and plate mills, began to replace traditional stone mills. Over the past century, small diesel engines have increasingly replaced reliance on manual mills. In countries with high electrification rates, mills have evolved again to exploit the availability of electricity. In Sub-Saharan Africa and South Asia, the low rate of electrification and lack of reliable electricity access have led to the continued widespread use of diesel engines for milling (Clarke B., 2006).

Many people still cannot afford paying for commercial grain-milling services and they grind by hand using traditional techniques. Therefore, pounding is a common sight and sound in many areas. It is often a social activity, carried out predominantly by women (Figure 2.), and many hours are spent each day in this laborious and time-consuming task (Clarke B., 2006).

The main objective of grain milling is to improve the digestibility of grain for human or animal consumption. Milling is often, though not always, preceded by other agricultural processes, such as drying, sorting, hulling, grating and polishing. All mechanical mills consist of a power source that drives a particle reduction mechanism. This can be through high-speed impact, such as hammer mills, or low-speed shearing forces, such as stone or roller mills.

According to Efficiency for Access Report, 2021, the primary performance metric for mills is throughput, typically measured in kg/hour. Throughput is directly proportional to power (kW) and energy (kWh). Where power is sufficient and affordable, it is easy to oversize mills to ensure high throughput, which leads to shorter customer waiting times. However, this can lead to high energy consumption and expensive underutilized mills, especially where there are high operational costs and an insufficient customer base. The report further stated that a mill's energy efficiency metrics can compare the performance of mills that differ in size, motor type, grinding mechanisms and configuration. Mill efficiency is measured by amount of product milled per unit of energy (kg/kWh). A variety of factors, including motor type, grain/produce moisture content and sieve hole diameter, influence the mill's efficiency. Efficiency is crucial, as efficiency gains directly translate to improved unit economics (. Elliot Avila, https://a2ei.org/news.). The ideal scenario optimizes efficiency and user-acceptable throughput for an accurately sized and affordable mill. An ideal scenario must balance three parameters: efficiency, throughput and cost. Cost can be further subdivided into capital and operational costs or viewed over the mill lifetime using lifetime cost analysis (Efficiency for Access Report, 2021).

- *Set up of Solar Milling Plant*

A Solar Milling Plant (SMP) in its basic form is designed to crush grains using mills powered by solar energy. It comprises three major sections:

- *Solar Panel Station and Modules:*

A solar milling plant consists of a solar panel station equipped with multiple solar modules. These modules are composed of solar cells, typically made of silicon, that convert sunlight directly into electricity through the photovoltaic effect. The solar modules are strategically arranged to maximize the capture of solar energy throughout the day.

- *Inverter:*

The electricity generated by the solar cells is in the form of direct current (DC). However, many industrial machines, including milling machines, operate on alternating current (AC). An inverter is a crucial component that converts the DC electricity produced by the solar modules into AC voltage, suitable for powering the machine's motor and other components.

- *Switch for Machine Control:*

A switch is used to regulate the operation of the milling machine. It allows the operator to turn the machine on and off as needed. This control mechanism ensures efficient energy usage and prevents unnecessary energy consumption when the machine is not in use.

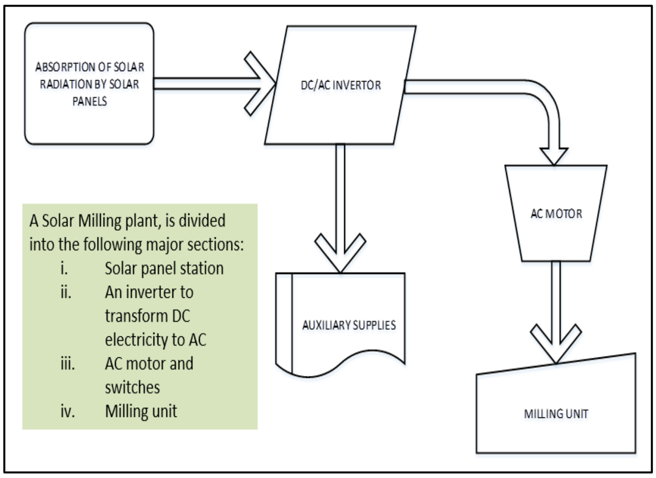

Fig 6 Schematic of Solar Milling Plant

- *Different Types of Milling Machines*

The major types of milling machines can be classified into either hammer mills or roller mills, with each type serving different purposes in the processing of materials.

- *Hammer Mills*

A hammer mill crushes materials as they are ground through the high-speed rotation of hammer tips. The fineness of the resulting material primarily depends on the size of the screen opening. The grinding effectiveness of the

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24APR2202

hammer mill is influenced by factors such as the volume of the rotor, the speed of the hammer tips, the quantity of hammers, and the size of the screen opening.

Figure 7 shows a typical Hammer Mill. They are very common throughout Africa. As the name implies, hammers in the mill grind grains through impact. A hammer mill consists of a large cylinder with a horizontal shaft that drives a rotor with several rows of free-swinging hammers. The hammers rotate inside a perforated metal screen through which the flour is drawn. The hammers are driven by two or four sets of V-section belts between the engine and the mill. The hammers spin at high speed, usually between 2 000 and 4 000 revolutions per minute to achieve a hammer-tip speed of about 60 m/second. The speed of the mill must be matched to the size of the mill as a small mill needs to run at higher revolutions than does a larger mill (Kosse, V., & Mathew, J. 2001).

A hammer mill's entire assembly is housed in a sheet metal enclosure. Grain is delivered through the casing's top aperture. The rotating hammers crush the falling grain, and milled bits are collected from the chute at the casing's bottom. The rotational orientation of the drum is often reversed to provide uniform wear of the hammer edges. Because the rods carrying the hammers are enclosed by hammers and space rings, they do not come into direct contact with the grain or milled particles, which could cause abrasive wear.

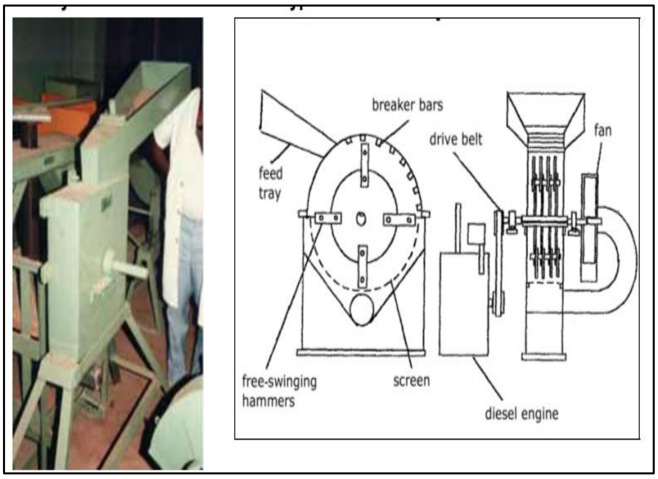

Fig 7 Hammer Mill Illustration (a) Physical Model (b) Drawing

- *Roller Mills*

Roller mills play a common role in preparing animal feedstock. These mills are comprised of two cylindrical steel rolls that rotate in opposite directions, each operating at distinct speeds. One of the rollers can be adjusted to vary the clearance between the roll corrugation, while the other roller remains fixed in the frame. The fundamental purpose of the roller mill is to break down the grain. This is accomplished by subjecting the grain to both shear and compressive forces. These forces are generated by the corrugation on the roll surface and the pressure exerted by the rotating rollers, pulling the particles towards the nip, as illustrated in Figure 8. This specific type of roller machine is employed in the preparation of wheat, sorghum, soybean, and corn for animal (cattle, poultry, and pigs) food. However, the demanding nature of the roller's work has implications for both the longevity of the rollers and the quality of the product, as noted by G.M. Campbell in 2007.

Roller mills are frequently used to grind wheat into flour in the flour milling business. A sequential grinding procedure is used to separate wheat bran from endosperm. Hammer mills, on the other hand, are mostly used for grinding feed. The energy efficiency of the roller mill is generally thought to be significantly higher than that of the hammer mill (Silver, 1931; Puckett and Daum, 1968; Appel, 1987).

For roller mill grinding, roll gap had the most significant effects on characteristics of the ground material and the energy requirement. It determined the final particle size of the ground material and the energy requirement.(Q. Fang, I. Bölöni, E. Haque, & C. K. Spillman1997)**.**

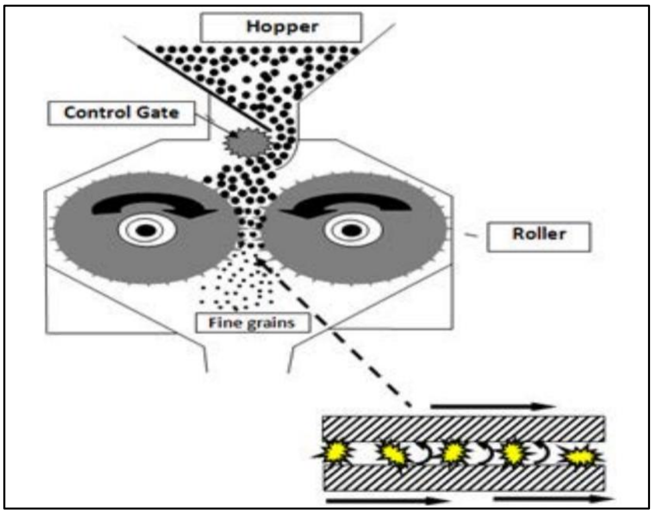

Fig 8 Schematic of Roller Grinding Machine, Source: Feng et al, 1997)

- *Economic Aspects of a Solar Milling Plant*

A study by Sanchit W. et al. (2018) revealed that Sub-Saharan Africa imports mills and mill components primarily from China and increasingly from India. Furthermore, the Asian milling market has a longer history of mechanization and is closer to the manufacturing base, but the markets are not homogenous. In India, for example, solar milling is a high-value rural income-generating activity (Sanchit W. et al., 2018).

According to the IFC Report (2019), standard on-grid solar mills are slowly replacing the large-scale diesel mills that dominated the off-grid market. The economics of small-scale agricultural processing (including milling) do not always make sense, whether they are solar-based or otherwise. Large-scale milling is currently limited to a few value chains that can supply the quantity of grain required for commercial viability. Aggregation provides much needed economies of scale, which brings down the unit cost

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24APR2202

of processing. The value proposition for solar milling is highest in remote areas where the distance to travel to existing mills is a greater challenge; however, the trade-off is that population density is lower in these areas. Additionally, in these remote areas, there may be competition from cheaper, incumbent small-scale diesel equipment that offers flexibility in terms of operational use and mobility.

- *Potential Benefits and Challenges of using Solar Energy for Maize Milling*

➢ *Benefits of using Solar Energy for Maize Milling*

- *Environmental Benefits:*

Solar energy is a sustainable and eco-friendly alternative to fossil fuels, significantly reducing greenhouse gas emissions and environmental degradation associated with traditional energy sources (International Renewable Energy Agency, 2020).

- *Economic Advantages:*

Over the long term, solar energy can lead to substantial cost savings due to lower operational expenses and reduced reliance on fluctuating utility prices. This can potentially result in increased profitability for maize milling operations (United Nations Environment Programme, 2019).

- *Energy Security:*

Solar power provides a reliable and decentralized energy source, reducing dependence on centralized grids and ensuring a steady power supply, especially in rural areas with unreliable electricity access.

- *Community Development:*

The adoption of solar energy for maize milling can stimulate local economic growth by creating job opportunities, fostering technological advancements, and enhancing energy access in underserved communities.

➢ *Challenges of using Solar Energy for Maize Milling*

- *High Initial Costs:*

The upfront investment required for purchasing and installing solar panels, inverters, and storage systems can be a barrier for small-scale maize milling operations, limiting widespread adoption (Sharma & Chandel, 2019).

- *Intermittent Nature of Solar Power:*

Solar energy generation is contingent on sunlight availability, leading to fluctuations in energy production and requiring efficient storage solutions to ensure uninterrupted milling processes, particularly during periods of low sunlight.

- *Technological Complexity:*

Maintaining and troubleshooting solar energy systems demands specialized technical expertise and training, which may pose challenges for operators unfamiliar with solar technology.

- *Regulatory and Policy Hurdles:*

In some regions, regulatory barriers, lack of supportive policies, or inadequate incentives for renewable energy adoption can impede the integration of solar energy into maize milling operations, hindering its full potential.

➢ *Impact on Communities*

In regions without grid electricity, the introduction of solar milling technology stands to revolutionize agricultural productivity and economic outcomes for farmers, particularly in securing the economic stability of rural communities that depend predominantly on agriculture. The process of grain production and its subsequent milling represent critical uses of energy for smallholder farmers in rural Africa, where a reliable, accessible energy source can be the difference between subsistence and a sustainable livelihood. Solar milling technology has the potential to reduce reliance on expensive diesel generators and provide a more sustainable and environmentally friendly alternative for farmers(Ghafoor, A. and Munir, A., 2015). By harnessing solar power for milling, farmers can increase their efficiency, reduce costs, and ultimately improve their overall quality of life.

Traditional diesel mills, with their large size and high operational and maintenance costs, are often unsuitable for serving small communities. They require a level of expertise that might be difficult to find in remote areas, resulting in these machines being more appropriate for larger market centers where such resources are more accessible and where their utility and output can be maximized.

The Food and Agriculture Organization's 2018 study illuminated the benefits of solar-powered mills, which provide a consistent energy source and can lead to significant reductions in operational costs. This affordability is key to empowering rural mill businesses to save money and improve the economic status of farmers. Additionally, solar mills contribute positively to health and environmental outcomes by diminishing dependency on diesel fuel, which is notorious for greenhouse gas emissions. In contrast, the emissions related to the production of solar batteries and panels are negligibly small, particularly in comparison with the ongoing emissions produced by diesel engines(Devabhaktuni.V. eta al., 2013). Overall, the long-term benefits of solar mills outweigh any potential environmental concerns. The transition to solar energy not only benefits rural mill businesses economically but also promotes sustainability and a healthier environment for all.

Nadji B's research in 2020 outlines the social impact of solar mills, revealing that women, who often bear the responsibility of food processing within households, can face extensive physical strains from tasks such as milling grains with traditional pestle and mortar techniques. This can lead to a range of health issues, from eye infections to chronic back pain. The introduction of mechanized milling systems like those powered by solar energy can significantly alleviate this physical exertion. Additionally, the use of solar mills can also empower women by freeing up their time for other activities, such as education or income-generating

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24APR2202

work. This not only improves their overall well-being but also contributes to gender equality and economic development in communities. By reducing the burden of manual labor traditionally placed on women.

Moreover, solar mills are designed with ease-of-use in mind, allowing operation and maintenance to be more accessible for women, who are typical mill operators in these communities. Simple innovations, such as replacing a strenuous hand crank with a starter switch, make a significant difference in usability. Furthermore, the reduced need to secure fuel for operation simplifies the process, decreasing the burdensome time required for milling. Not only does this make the technology more attractive and usable, but it also frees up considerable time for women and girls, who can then direct this time towards furthering their education or engaging in other productive economic activities. This change can contribute to broader social benefits, including educational advancement and economic empowerment for women and girls within these communities. All these aspects underscore solar milling's potential as a transformative tool for sustainable development in rural areas. Additionally, by reducing the reliance on fossil fuels, solar milling also helps to mitigate environmental impacts and promote a cleaner, more sustainable future for all.

➢ *Description of Cropping Systems and Climate in Zambia*

In Zambia, the agricultural sector provides a living for 85% of the population. Maize is both the main cash crop (>65% of cropped land) and the main staple crop. Maize consumption per capita is estimated to be 105 kilograms per year, with most of it ground into meal and consumed as stiff porridge, or fermented for beer, with byproducts used as livestock feed. Agriculture, unlike elsewhere in Sub-Saharan Africa, is relatively unimportant in Zambia's economy when compared to mining (primarily copper). It accounts for less than 20% of the gross domestic product. However, Zambia has significant potential for increased agricultural output; currently, less than 30% of potentially arable land is cultivated. Historically, the agriculture sector has been hampered by low product prices, difficulties in obtaining and distributing credit and inputs, and a lack of foreign exchange (R. Chiwowo, Yieldgap-2020).

According to the amount of land that each farmer cultivates, Zambia has three main categories of farmers. Many small-scale farmers cultivate less than five ha, use few outside inputs, consume most of their harvest, and occasionally sell any surplus produce in the market. The hand hoe is the most common cultivating tool. 5 to 20 ha are under cultivation by medium-sized farmers. They sell much of their production while using improved fertilizers and seeds. These farmers frequently mix tractors, manual labor, and animal draft power. Every year, large-scale commercial farmers plant more than twenty ha. These farmers work their farms with oxen or machinery and a lot of purchased inputs. They almost exclusively produce for direct market sales or to feed the farm's own livestock with grain. Only 4% of farm households are large-scale farmers, but they work 22% of all croplands.

- *Production and Yield*

Crop yields depend on the production circumstances, with higher yields on commercial farms and lower yields on small-scale farms. Annual maize production in Zambia was on average 1.1 Mt from 2000 to 2010, and average yields of about 1.5 t/ha that have not significantly changed over the past 20 years. Cultivated maize area has been on average 700,000 ha between 1987 and 2007, with largest area of 900,000 ha in 2008. The yield gap between actual yields and potential yields remains wide. Zambia produced an annual average of about 24,000 metric tons of sorghum and 42,000 metric tons of millet between 1987 and 2008.

- *Agro-Ecological Zones*

Zambia is divided into three main agro-ecological regions, based on rainfall amount and other climatic characteristics. Region, I cover areas of southern, eastern, and western Zambia, with an annual rainfall of 600-800 mm. The growing season is short, at 80-120 days, and is risky for crop production, as poorly distributed rains often result in crops enduring frequent dry spells. Region II includes most of central Zambia, with fertile soils and most of Zambia's commercial farms. It has been further subdivided into IIa and IIb sub-regions, based on annual rainfall. Average rainfall in Region II is 800-1000 mm, and the growing season is 100-140 days long. Distribution of rainfall is not as erratic as in Region I, but dry spells are common and reduce crop yields, especially on the sandier soils. Average mean daily temperatures range from 23- 26°C in the hottest month October to 16-20°C in the coldest months of June and July. The most common soils in Region II are red to brown clayey to loamy soil types that are moderately to strongly leached. Physical characteristics of the soils that affect crop production, include low water holding capacity, shallow rooting depth, and topsoils prone to rapid deterioration and erosion. These soils also have low nutrient reserves and retention capacity, are acid, have low organic matter and nitrogen content, and are phosphorus deficient.

Region III, which is known for its high rainfall, covers parts of northern Zambia, including the Northern Luapula Copper belt, Northwestern provinces, and some parts of the Central province. This area receives over 1000 mm of precipitation each year, and the growing season ranges from 120-150 days. The soils in Region III are highly weathered and leached and are very acidic.

- *Major Cropping Systems*

Region I is mostly made up of small-scale farmers who live in the valley systems in the Luangwa Valley. They grow starchy foods like sorghum, finger millet, and maize. They also grow groundnuts, cowpeas, and pumpkins. Some farmers keep goats and chickens, while others only have cattle.

Zambia's commercial farmers are concentrated in Region II. They specialize in growing maize, soybeans, wheat, cotton, tobacco, coffee, vegetables, and flowers. There are also small- and medium-scale farmers in the region who grow other crops, like beans, groundnuts,

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24APR2202

pumpkins, and cassava leaves. The main constraints to increasing crop production in Region II are the lack of low-cost biocides to control pests and diseases, soil degradation, and the depletion of soil fertility.

➢ *Agricultural Maize Production in Zambia*

In Zambia, maize is the most important crop. Maize (Zea mays L.) originates from Latin America. Its cultivation is thought to have begun as early as 3000 BC. Maize piqued the interest of Christopher Columbus, who arrived in Cuba in 1492 on his voyage to discover the Americas. The crop he brought back to Spain quickly spread around the Mediterranean rim before being introduced to West and East Africa in the 16th century.

As an African original product, sorghum (Sorghum bicolor (L.) Moench) and millet (Eleusine Coracana Gartner) were the Zambian staple crops at the time but were gradually replaced by maize. When the country gained independence in 1964, maize already accounted for more than 60% of the planting area of major crops. The planting area and production volume of maize increased rapidly, particularly in the 1970s, as the government introduced chemical fertilizer subsidy programs and raised the producer price in 1970.However, due to droughts in 1979 and 1980, production volume plummeted and has not recovered since, despite the spread of hybrids.

Meanwhile, sorghum and millet production, which had been the mainstay of Zambian diet for millennia, fell by two-thirds and nine-tenths, respectively, during the 1970s.The spread of hybrids has had no effect on maize unit yield, which now stands at 1.8t/ha, which is comparable to traditional varieties. This could be because many subsistence farmers cannot afford new hybrid varieties and instead use recycled hybrid seeds. Chemical fertilizer prices are also too high to allow for adequate fertilizer application, which may explain the low unit yield. Zambia, according to reports, requires 1.2 million tons of maize to ensure self-sufficiency.

In terms of production, maize is a common crop cultivated by smallholder farmers and is the main food source in the country. Zambia generated its highest corn yield on record in the 2021/22 MY. Compared to the 3.4 million tons of corn produced in the 2020/21 MY, this bumper crop of 3.6 million tons is seven percent larger. Zambia became a net exporter of corn over the past 20 years by more than doubling corn production through an increase in area and productivity. In the MY2021/22, according to Post, Zambia will consume roughly 2.4 million tons of grain.

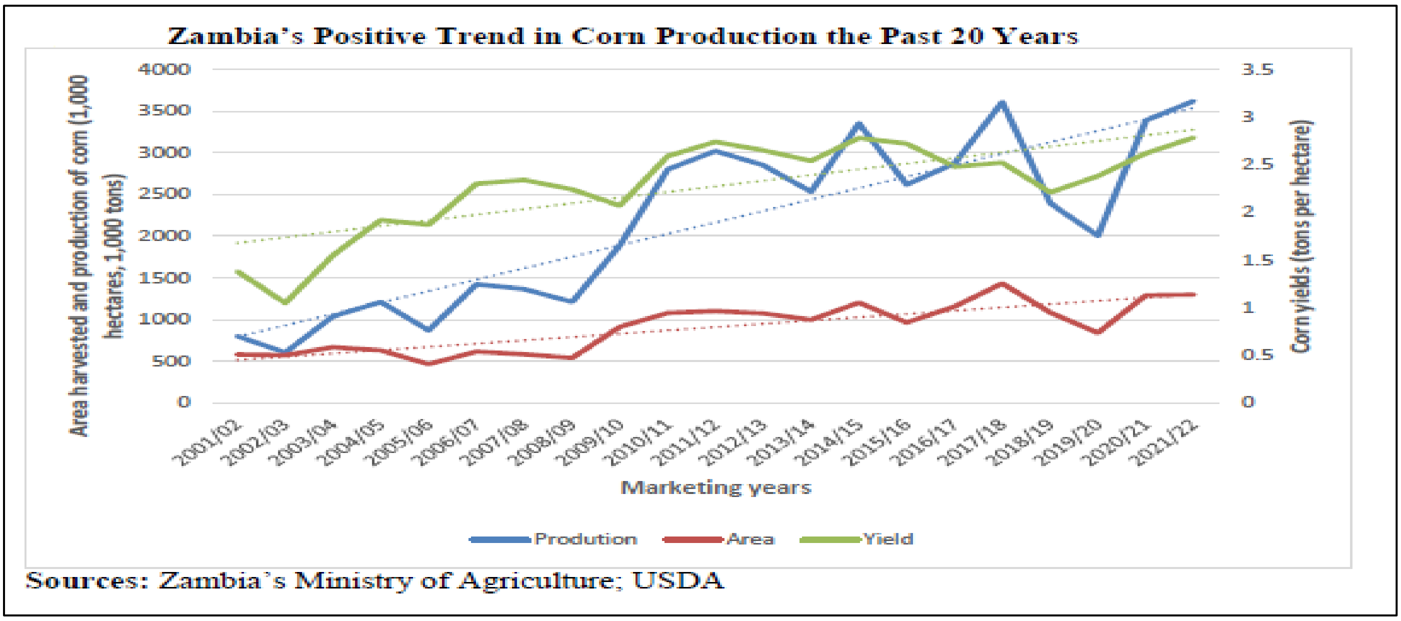

Fig 9 Zambia's Maize Production Trends

The following table details how much each of Zambia's ten provinces contributed to the nation's total area and corn output in the 2019–2020, 2020–21, and 202–22 MYs (see also map of Zambia below).

All 10 provinces of Zambia produce corn, but more than half of it is grown in the Central, Eastern, and Southern provinces. In the 2021/22 MY, the Eastern province was the major producer of corn with 724,000 tons or 20 percent of total corn production. The Southern province contributed more than 20 percent to the total area of corn planted in Zambia and produced the second largest corn crop at 616,000 tons in the 2021/22 MY.

III. RESEARCH METHODOLOGY

➢ *Research Approach*

The study encompassed a combination of qualitative and quantitative data. The research took a mixed approach, incorporating extensive literature reviews to gain a broader understanding of the topic. Structured questionnaires were utilized to collect the data.

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➢ *Study Site*

The study was carried out in the 12 sites of Masaiti, Solwezi, Kapiri Mposhi and Chikankata Districts were the milling plants were installed.

➢ *Research Population*

The population for this study was the community members, solar milling plant operators and the cooperative leaders from the 12 sites of Masaiti, Solwezi, Kapiri Mposhi and Chikankata Districts were the solar milling plants were installed**.**

➢ *Sample Size*

The sample Size for the study was 168 comprising of operators, cooperative leaders and community members. 5 cooperative leaders and 5 community members were targeted from each of the 12 sites bringing the total number for each to 120 (60 each). Further, 4 operators were targeted from each of the 12 sites bringing the number to 48. The 48 operators, 60 community members and 60 cooperative leaders brought the total sample size to 168.

➢ *Types of Data*

- *Technical Data*

Technical data collected on site included measurements of power output, temperature, and irradiation. Additional technical data was gathered through a questionnaire, which covered the following:

- ✓ Determining the proximity of the solar milling plant to the closest village.
- ✓ Evaluating the operator's understanding of the operational needs of the milling plant.
- ✓ Collecting data on the average daily maize processing capacity of the Solar Milling Plant.
- ✓ Collecting data on the monthly occurrence of breakdowns at the Solar Milling Plant.
- ✓ Assessing the accessibility of spare parts for the Solar Milling Plant as perceived by its operators.
- ✓ Collecting data on the daily operating times of the SMP. When do they start and when do they stop operating?

- *Social and Economic Data*

The questionnaire collected social and economic data on;

- ✓ The community members' willingness to use the solar milling plant for processing maize.
- ✓ The monthly revenue generated by the Solar Milling Plant (SMP).
- ✓ The typical travel time taken by the community members to access the solar milling facility.
- ✓ The community's interest in mealie meal produced by the solar milling plant.
- ✓ The frequency of maize delivery to the solar milling plant by community members.
- ✓ Evaluating the dependability of mealie meal supply from solar milling plants in the local market.
- ✓ Assessing the effects of SMP-produced mealie meal on pricing in local communities.
- ✓ Assessing the impact of Solar Milling Plants on employment opportunities.

- *Environmental and General Data*

The questionnaire collected general and environmental data, focusing on;

- ✓ Confirming participants' awareness of the benefits of solar milling plants through education.
- ✓ Evaluating the perception of direct advantages from solar milling plants in the vicinity.
- ✓ Exploring the anticipated benefits of living near solar milling plants on livelihood improvement.
- ✓ Assessing participants' comprehension of the factors driving the installation of solar milling plants.
- ✓ Assessing the level of engagement of the participants in the survey.
- ✓ Assessing the impact of Solar Milling Plant installation on community displacement.
- ✓ Exploring the effects of Solar Milling Plants on deforestation.
- ✓ Evaluating the impact on natural habitat and wildlife, considering the land used for renewable energy.
- ✓ Assessing the participant's current employment situation.

➢ *Specific Objectives and Methods*

- *Establishing Technical Operational Characteristics of Installed SMPs*

This was done through purposive sampling guided one-on-one interviews with SMP operators focusing on critical operational details, including power consumption, revenue, milling frequency, and daily output among other things.

- *Investigating Technical Operational Characteristics of SMPs*

This was accomplished by utilizing a specific section of the questionnaire that pertains to SMP operators. The focus was on skill levels and hours of operation.

- *Analyzing Factors Influencing Plant Siting*

Site interviews covered as part of the questionnaire with cooperative leaders formed the basis for understanding the strategic decisions behind the siting of SMPs. Some valuable information was also obtained from ZCF leaders.

- *Assessing Economic Benefits from SMPs*

Comprehensive data on economic benefits was obtained through site visits and structured questionnaires within the community. The section of the questionnaire that focused on the economic assessment also considered the influence of sales returns on the overall economic sustainability of SMPs.

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- *Benchmarking Technical Operating Conditions for the Installed SMPs*

To assess the operational parameters of the installed Solar Milling Plants (SMPs), a thorough evaluation of primary and secondary data was undertaken. This comprehensive approach facilitated the identification of practical recommendations aimed at ensuring the smooth and optimal operation of SMPs.

➢ *Tools Utilized*

Data collection methods included field visits and questionnaires interviews which were conducted through both individual and group discussions.

The NASA Power-Data Access viewer was used to collect irradiance and temperature data for the sites as part of the technical data collection process. Measurements of current and voltage were obtained by using a current amp meter and a multimeter. The power output was determined by measuring the voltage and current.

➢ *Data Analysis*

The data collected from the questionnaire was subjected to statistical analysis using SPSS. This analysis involved examining frequencies, summarizing data, and performing Chi-square tests to evaluate the technical performance and economic advantages of the Solar Milling Plants (SMPs). Moreover, Excel was used to study the fluctuations in power and irradiance based on data gathered during field surveys.

➢ *Ethical Consideration*

The researcher sought the ethical clearance of the research respondents before proceeding to engaging them in the study. The research participants were assured that they information they provided would be kept confidential and only used for academic purposes only.

IV. DATA PRESENTATION AND ANALYSIS

The data was collected using field observations and semi-structured questionnaires, providing a comprehensive overview of the primary information gathered during the research process. The field measurements and observations were instrumental in obtaining crucial data, including measurements for maximum radiance, maize grilling capacity per day, power capacity, SMP operation time, number of operators, and PV module sizing. This obtained data played a crucial role in benchmarking the operational routines of the solar milling plants. Additionally, the semi-structured questionnaire was employed to gather perspectives from community members, cooperative leaders, and operators regarding the technical and economic performance of the milling plants. The questionnaire included multiple-response questions, some utilizing a Likert scale, while others were closed-ended, prompting respondents to provide their own detailed responses.

The chapter is structured into four sections, addressing the response rate, demographic profile of the research respondents, data obtained through benchmarking observation, and data obtained through the semi-structured questionnaire.

➢ *Response Rate*

This study aimed to engage operators, cooperative leaders, and community members across 12 sites in Zambia, including Solwezi District, Masaiti District, Kapiri Mposhi District, and Chikankata District.

The targeted participants totaled 168, encompassing cooperative leaders, community members, and operators from all the sites. Table (1) below provides details on the sample size composition for the study and indicates the corresponding response rate.

Table 1 Response Rate

Respondents	Target	Responded	Response rate (%)
Operators	48	40	71.4
Community members	60	40	
Cooperative leaders	60	40	
Total	168	120	

Table (1) above indicates a favorable response rate of (71.4%) for this study. The generated responses affirm that the study achieved a commendable response rate, demonstrating its representativeness of the target population.

➢ *Demographic Profile*

This section presents the generated results on the gender and employment status of the respondents who took part in this study as shown in (figure 10 & figure 11) below

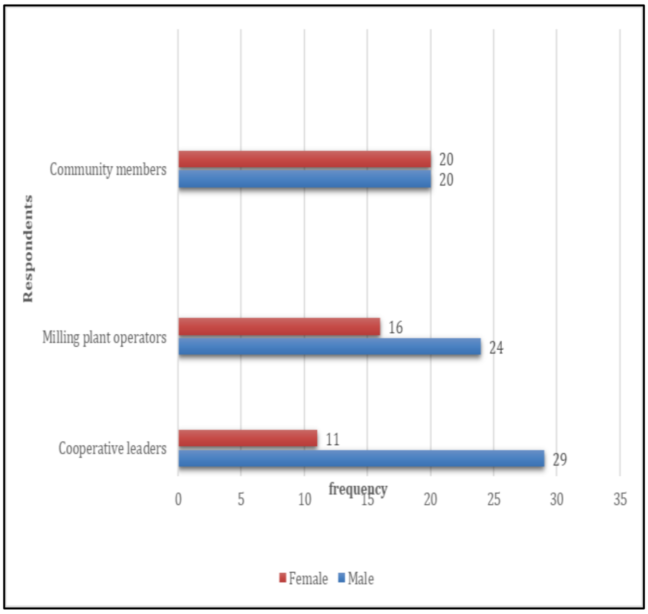

Fig 10 Gender

Figure (10) visually represents the gender distribution of community members, solar milling plant operators, and cooperative leaders who participated in this study. The data reveals that among the community members, there were 20

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males and 20 females. For solar milling plant operators, the generated results indicate 16 females and 24 males. Among cooperative leaders, the data shows 29 males and 11 females. It is evident from the results that both milling plant operators and cooperative leaders were predominantly males.

It is worth noting that while the gender distribution leans towards males in both roles, this could be attributed to societal norms, where by traditionally in Zambia Milling plants are run by men.

The generated results in figure (11) below shows that all the milling plant operators (40) and the cooperative leaders (40) who took part in this study were employed. The generated results also show that most (28) were unemployed. Only (12) of the community members were employed.

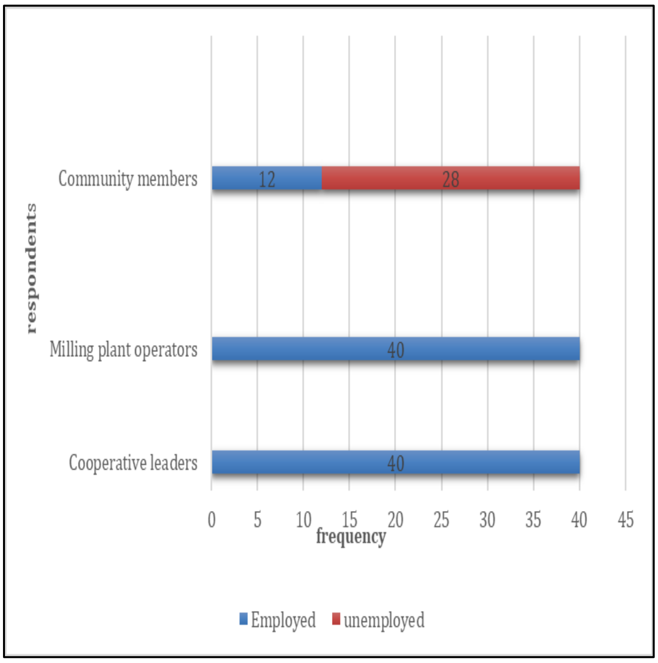

Fig 11 Employment Status

- *Presentation of Data Obtained Through Benchmarking Observations*

This section presents the data obtained through benchmarking observations conducted across the 12 sites in Chikankata, Solwezi, Masaiti, and Kapiri Mposhi Districts. The study strategically distributed sites, with Sites 1-3 in Solwezi, Sites 4-6 in Masaiti District, Sites 7-9 in Kapiri Mposhi District, and Sites 10-12 in Chikankata District. Each site's benchmarking data includes critical observations and measurements related to solar milling plant operations. Notably, the distribution of solar milling plant operators and cooperative leaders, along with technical parameters like maximum radiance, maize grilling capacity, power capacity, SMP operation time, and PV module sizing, were meticulously recorded. The comparative analysis across all sites reveals insights into regional variations and operational trends. The findings not only present a detailed snapshot of the current state of solar milling plants but also lay the groundwork for recommendations aimed at optimizing operational efficiency and addressing observed challenges. Additionally, the data serves as a valuable resource for future considerations, suggesting potential areas for further research and improvement in the solar milling industry.

Figure (12) presents the latest data on critical metrics for solar milling plants across the 12 surveyed sites. The findings indicate a uniform configuration with each site having two operators and a consistent minimum power capacity of (7.5kW). Additionally, all 12 sites exhibited the same PV module sizing, recording (15.3kW) as installed capacity. However, variations were observed in SMP operation time. Site 1 registered the highest operation time at (9hrs), showcasing robust performance, while sites 2, 7, and 9 reported the lowest operation time at (6hrs).

This updated dataset underscores the operational uniformity in terms of manpower and technical specifications across the surveyed solar milling plants. The distinct SMP operation times highlight potential areas for improvement or optimization, providing valuable insights for stakeholders in the solar milling industry.

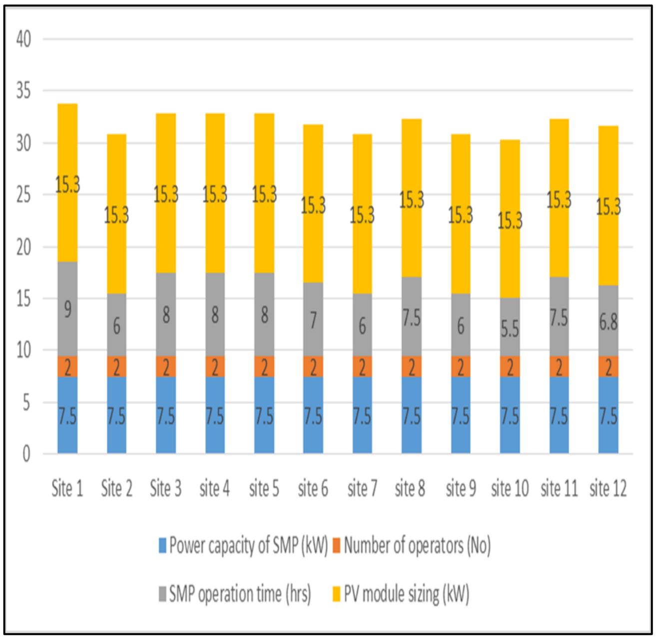

Fig 12 Minimum Power Capacity, SMP Operation Time, Number of Operators and PV Module Sizing

Figure (13) below displays data on the maximum irradiance and daily maize grains grilling capacity. The findings indicate a range in maximum irradiance from 498.009W/m2 to 506.602W/m2. Site 10 achieved the highest maximum irradiance at 506.602W/m2, while Site 4 recorded the lowest at 498.009W/m2. Additionally, the data reveals a range in daily maize grains milled, varying from 300kg to 550kg. Site 4 exhibited the highest daily maize grains milling capacity at 550kg, contrasting with Site 9, which had the lowest daily output at 300kg.

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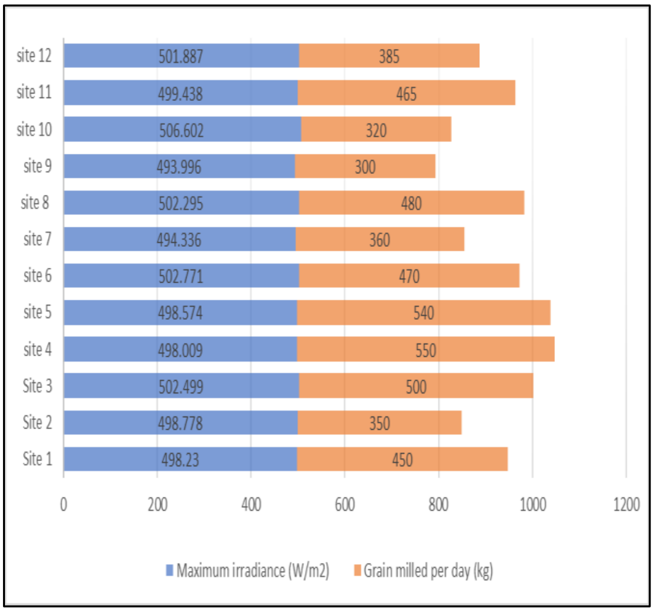

Fig 13 Maximum Irradiance and Maize Grain Grilled per Day

➢ *Presentation of Data Obtained Through the Semi-Structured Questionnaire*

As previously indicated in the introductory section of this chapter, a semi-structured questionnaire was utilized, encompassing a range of open and closed-ended inquiries that delved into the technical and economic performance of solar milling plants. Some questions within the questionnaire were exclusively designed for multiple responses and did not adhere to the Likert scale structure. These were presented in the form of frequency and percentage distributions. Questions following the Likert scale structure will undergo analysis using descriptive statistics and the chi-square test of association. Consequently, this section will commence by presenting the data derived from questions featuring multiple responses and closed-ended formats, excluding those employing the Likert scale.

- *Presentation of Data on Non-Likert Scale Multiple Response Questions and Closed Ended Questions.*

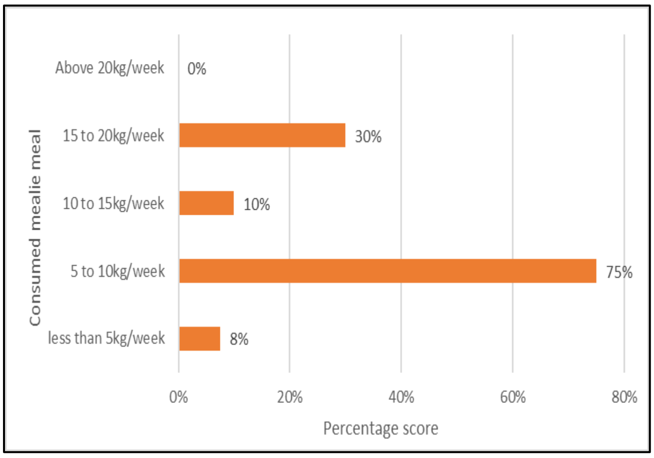

Fig 14 Mealie Meal Consumption per Week by Community Members

Figure (14) above shows the percentage distribution of the mealie meal consumed on a weekly basis by the community members who took part in this study. From the results generated, most (75%) of the community members consumed (5-10kg) per week. The results generated also shows that none (0%) of the community members consumed above (20kg) of mealie meal per week.

Figure (15) below shows the frequency distribution of the kilograms of maize that the community members who participated in this study took for milling monthly. The generated results show that most (15) of the community members took (25-30kg) of maize grain for milling monthly. The community members who took (above 30kg) for milling in a month were the fewest (1).

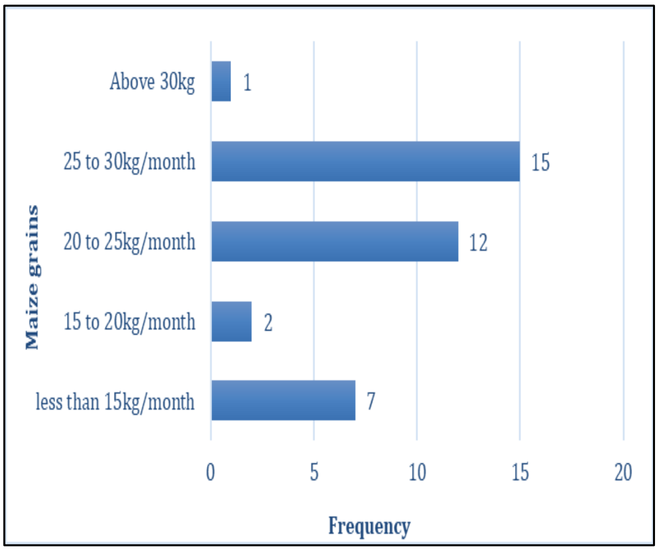

Fig 15 Maize Grain Milled in a Day from the Milling Plant by Community Members

Figure (16) below shows the frequency distribution of the revenue generated in a week by the milling plant operators that took part in this study. The obtained results show that most (16) of the milling plant operators generated (350k-450k) as weekly revenue. The generated results also show that none of the milling plant operators that took part in this study generated week revenues above (550k)

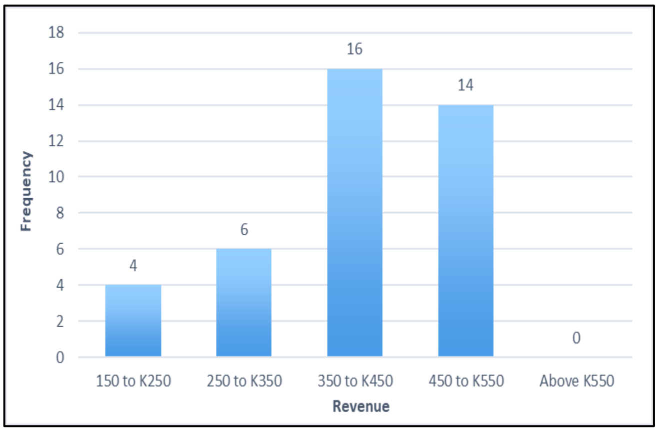

Fig 16 Revenue Generated in a Week by Milling Plant Operators

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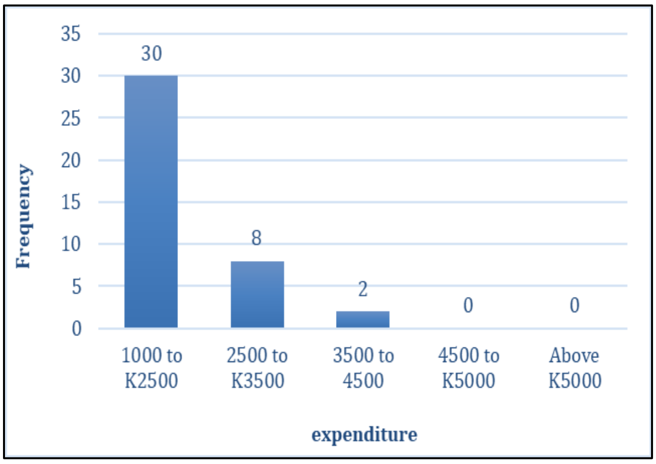

Fig 17 Money Spent on Spares/Repairs Monthly by Milling Plant Operators

Figure (17) above shows the results generated on the money spent by the milling operators on repairs monthly. The obtained results show that most (30) of the milling operators that took part in this study spent (k1, 000-k2, 000) on repairs. The generated results also show that none (0) of the milling plant operators who took part in this study spent either (k4, 500-k5, 000) or (above k5, 000) on repairs monthly.

Figure (18) below shows the frequency distribution of the kilograms of maize produced for supply to the local market by the milling plant operators that took part in this study. The generated results show that most (24) of the milling plant operators produced (less than 50kg) of mealie meal for supply to the local market. The generated results also show that none of the milling plant operators that took part in this study produced (above 500kg) of mealie meal for supply to the local market.

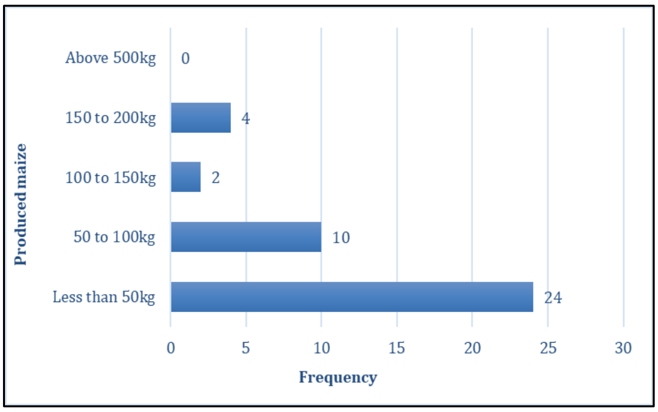

Fig 18 Kilograms of Mealie Meal Produced for Supply to the Local Market

The results generated by figure (19) below shows that most of the solar milling plant operators were of the view that the solar milling plant processed (60kg-100kg) of maize in a day. Further, the generated results show that none (0) of the solar milling plant operators were of the view that the milling plant processed either (10kg-50kg) or (above 50kg) of maize in a day.

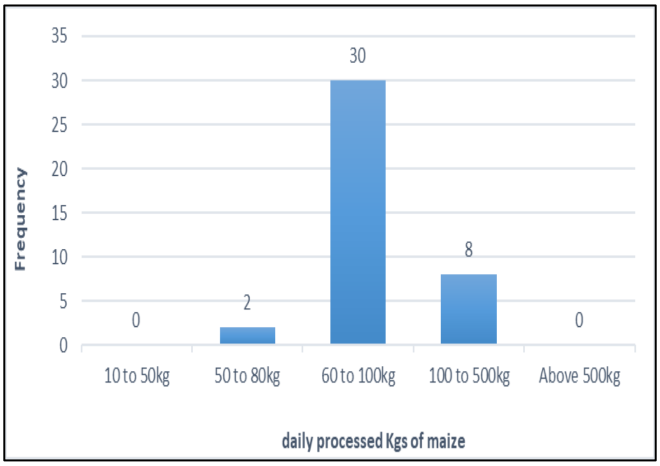

Fig 19 SMP Operators view on the Kgs of Maize the Milling Plant Processes in a Day

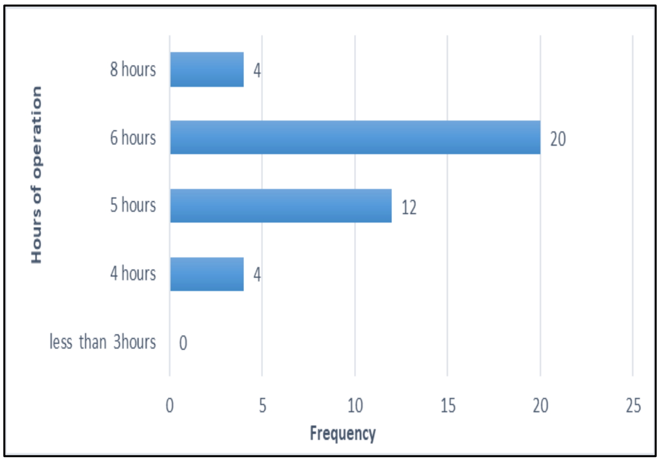

Fig 20 SMP Operator's views on the Hours of Operation of the Solar Milling Plant,
Source: Author, 2024

Figure (20) above shows that most (20) of the solar milling plant operators were of the view that hours of operation of the solar milling plant was (6hours). The generated results further show that none (0) of the solar milling plant operators were of the view that the hours of operation for the solar milling plant was (less than 3hours).

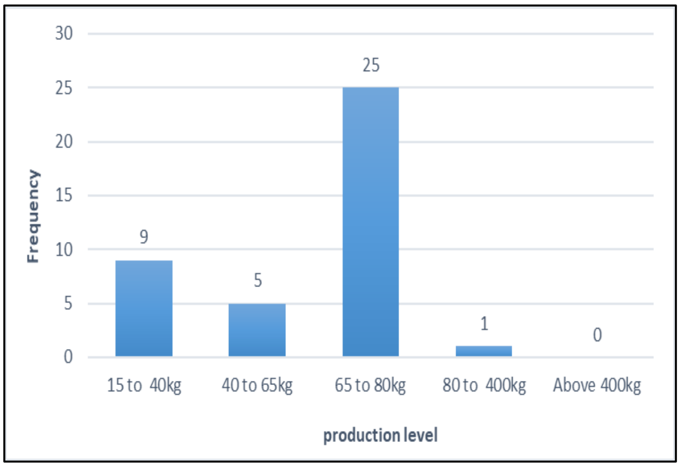

Fig 21 SMP Operator's Views on Production at Minimum Power

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24APR2202

Figure (21) above shows that most (25) of the solar milling plant operators were of the view that at minimum production power, the solar milling plant was able to process (65k-80kg) of maize. The generated results also show that none (0) of the solar milling plant operators were of the view that the solar milling plant was able to process (above 400kg) of maize at minimum production power.

The results generated in figure (22) below shows that most (30) of the milling plant operators were of the perception that at maximum production power, the solar milling plant was able to process (100kg-500kg) of maize. The generated results also show that none (0) of the solar milling plant operators were either of the view that at maximum production power, the solar milling plant processed (25kg-50kg) or (50kg-75kg) of maize.

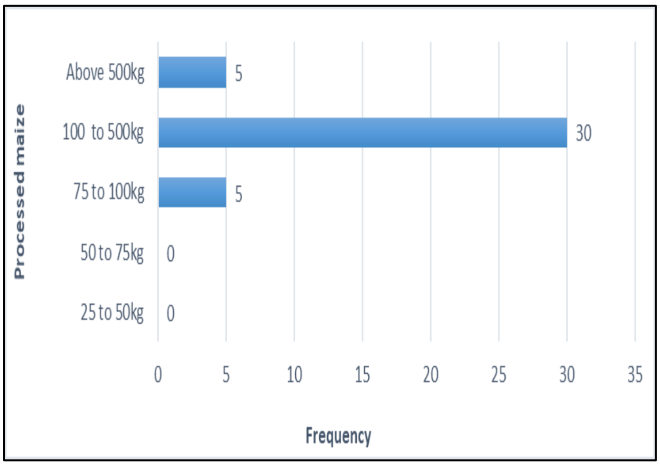

Fig 22 SMP Operator's Views on Production at Maximum Power

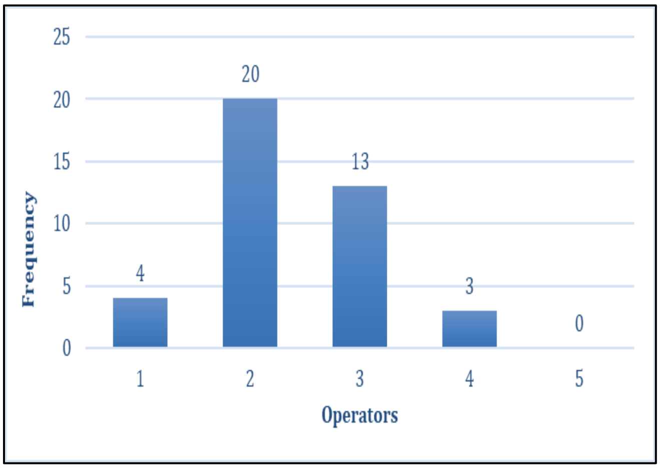

Fig 23 Number of Operators Employed to Run the Milling Plant by Cooperative Leaders

Figure (23) above shows the frequency distribution of the number of operators employed by ZCF to run the milling plant. The generated results show that most (20) of the cooperative leaders strongly agreed that (2) operators were employed to run the milling plant. The generated results also show that none of the cooperative leaders strongly agreed that ZCF had employed (5) operators to run the milling plant.

Table 2 SMP Operator's Perspectives on Minimum and Maximum Operation Power

Variable	Capacity	Frequency
Minimum power for operation	7.5kW	40
Maximum power for operation	9.0kW	40

Table (2) shows the maximum and minimum power operation of the solar milling plant as provided by the SMP operators. The generated results from the table shows that all (40) of the SMP operators that took part in this study were of the view that the minimum power for operation was (7.5kW) while the maximum power was (9.0kW)

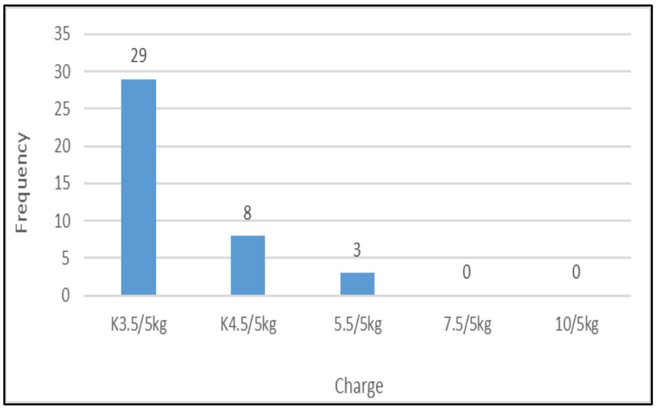

Fig 24 Views of Cooperative Leaders on the Charge for Milling Grain

Figure (24) above shows the frequency distribution of the views of the cooperative leaders on the charge for milling grain. The generated results show that most (29) of the cooperative leaders were of the view that the charge for milling grain was (k3.5/5kg). The results generated also shows that none (0) of the cooperative leaders were of the view that the charge for the milling grain was either (k7.5/5kg) or (k10/5kg)

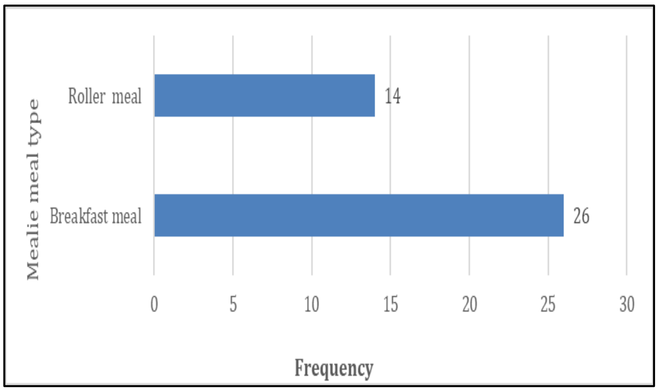

Fig 25 Views of Cooperatives Leaders on the Major Types of Mealie Meal Milled

Figure (25) above shows the frequency distribution of the views of the cooperative leaders on the major types of mealie meal milled. The generated results show that most (26) of the cooperative leaders were of the view that the major type of mealie meal milled was breakfast. Only (14) of the cooperative leaders were of the view that roller meal was the major type of mealie meal milled.

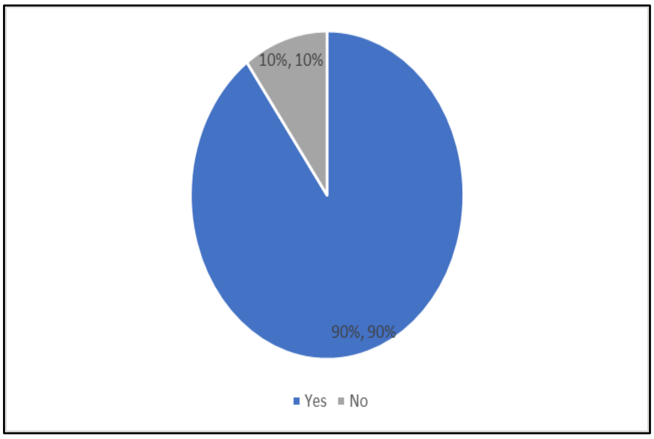

Fig 26 Views of Cooperative Leaders on Whether the Milling Produces by Products

Figure (26) above shows the views of the cooperative leaders on whether the milling plant produced any byproduct. The generated results show that most (90%) of the cooperative leaders were of the view that the milling plant produced byproducts. Only (10%) of the cooperative leaders were not of the view that the milling plant produced byproducts.

Figure (27) below shows the generated frequency distribution results of the views of the cooperative leaders on the price of mealie produced from the milling plant. The generated results show that most (19) of the cooperative leaders were of the perception that the price of mealie meal produced by the milling plant was (k250/25kg). The generated results also show that none (0) of the cooperative leaders were of the perception that the price of the mealie meal produced by the milling plant was (above k350/25kg)

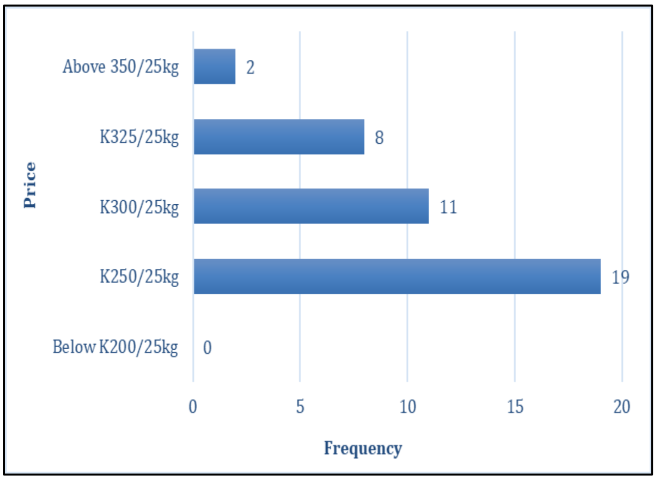

Fig 27 Views of Cooperative Leaders on the Price of Mealie Meal Produced, Source

The generated frequency distribution on the price of byproducts produced by the milling plant in figure 28) below shows that most (21) of the cooperative leaders were of the view that the price was (k30/25kg). The generated results also show that none (0) of the cooperative leaders were of the view that the price of the byproducts generated by the milling plant were (k50/25kg)

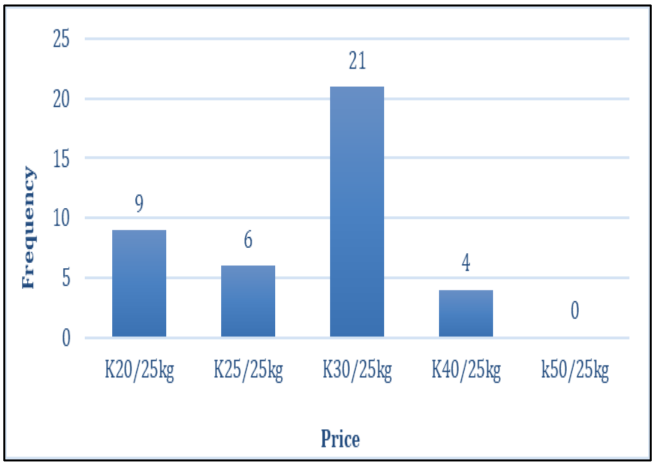

Fig 28 Views of Cooperative Leaders on the Price of by Products Produced by the Milling Plant

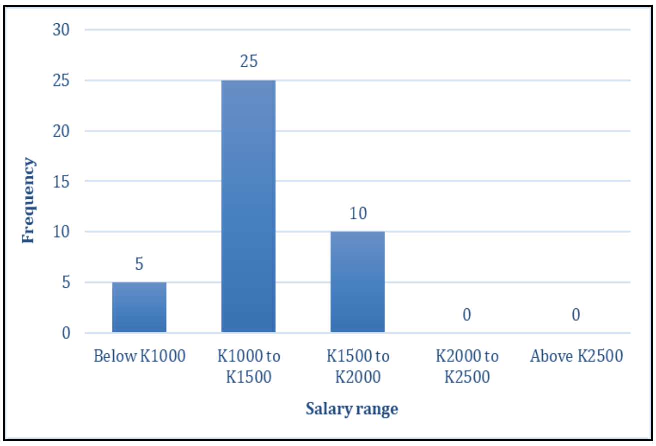

Fig 29 Views of Cooperative Leaders on the Salary Range of Milling Plant Operators

Figure (29) above shows the frequency distribution of the views of the cooperative leaders who took part in this study on the salary range of the milling plant operators. The obtained results show that most (25) of the cooperative leaders were of the view that the salary range for milling plant operators was (k1, 000-k1, 500). The generated results also show that the cooperative leaders were of the view that none (0) of the milling plant operators generated salaries ranging either (K2, 000-k2, 500) or above (K2, 500)

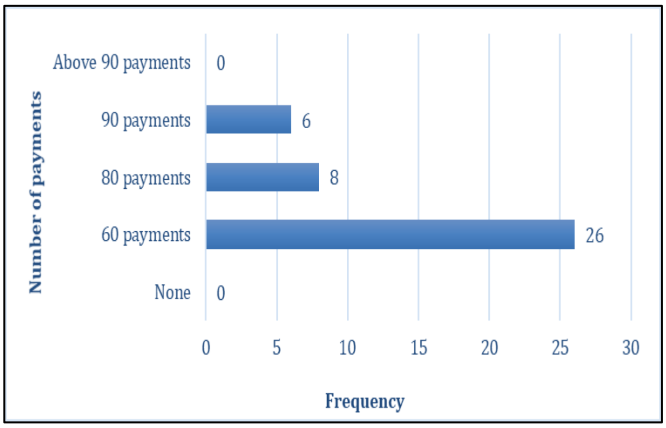

Fig 30 Views of Cooperative Leaders on the Number of Payments Towards the Loan

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24APR2202

Figure (30) above shows that most (26) of the cooperative leaders who took part in this study agreed that above 60 payments had been made towards the loan payment for the milling plant project. The generated results also show that none (0) of the cooperative leaders were of the perception that no payments or payments above 90 were made towards the loan.

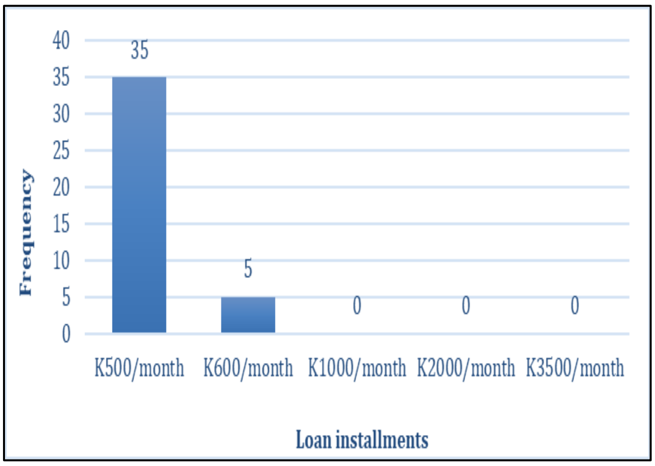

Fig 31 Views of Cooperative Leaders on Loan Installment Rate, Source: Author, 2024

Figure (31) above shows that most (35) of the cooperative leaders who took part in this study were of the opinion that the loan installment rate for the milling plant project was (k500/month). The generated results also shows that none (0) of the cooperative leaders were of the opinion that the loan installment rate was (K1, 000/month, K2, 000/ month and k3500/month)

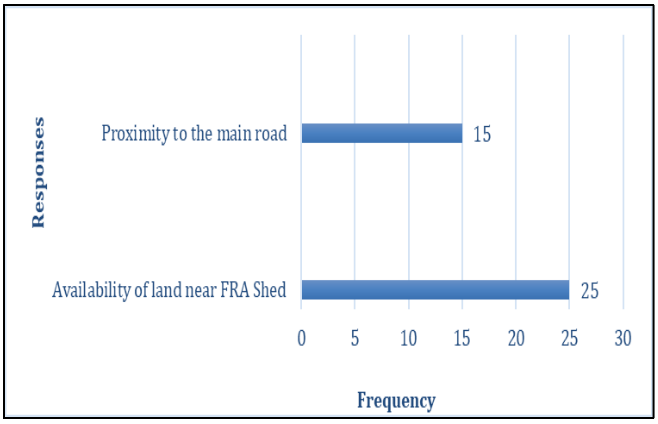

Fig 32 Cooperative Leader's Views on why the Milling Plant Locations were Considered

Figure (32) shows that the cooperative leaders were of the view that the two main reasons that influenced the setting up of the milling plants in their respective locations were proximity to the main road and availability of land near FRA shed. Of these two reasons, most (250) of the cooperative leaders were of the view that availability of land near the ZRA shed was the principal factor that influenced the setting up of the milling plants in their respective locations

- *Descriptive Statistics*

This section of the chapter presents and analyzes data from the questions in the questionnaire that took the Likert scale route. The main statistics of interest were the mean scores generated by each question and the weighted average mean or grand mean. The research questions under each variable which had a mean score less than the weighted average mean were taken to imply low perception or agreement. Further, the research questions under each variable which had a mean score greater or equal to the weighted average mean were taken to present high perception or agreement to each research construct by the respondents.

The generated descriptive statistics as guided by the average weighted mean (2.92) shows that the cooperative leaders and operators were of a high perception that operators received training before the installation of the solar milling plants (mean=3.57), operators at the milling plant were competent (mean=3.35) and that the solar milling plant experienced breakdowns (mean=3.65). However, the cooperative leaders and operators were of a low perception that the solar milling plant was located close to the community (mean=2.43) and that there was availability of spare parts for the solar milling plants (mean=1.63)

The descriptive statistics on socio-economic benefits of the solar milling plants in table (4.4) above showed that the cooperative leaders and community members were of a high perception that community members were willing to mill at the milling plant (mean=1.17), cooperatives bought maize from the milling plant (mean=3.12), there were benefits in the solar milling plants being located close to the communities (mean=3.95) and that the community members would benefit from the solar milling plants being located close to them (mean=4.15).

However, the generated results in table (4.4) above also shows that the cooperative leaders and community members were of a low perception that the time taken to reach the milling plant by the community members was short (mean=2.13), price for maize grain at the milling plant favorably compared with the local market (mean=2.65), solar milling plant was insured (mean=2.08) and that the community members were educated on the benefits of the milling plant (mean=2.00)

The generated results showed that the cooperative leaders were of a high perception that the installed milling plant was near FRA (mean=4.35), there was deforestation (mean=3.30) and displacement of the people during the installation of the solar milling plant (mean=3.25). However, the generated results also show that the cooperative leaders were of a lower perception that there was displacement of world life during the installation of the solar milling plant (mean=2.40).

- *Chi-Square Test for Association*

This section assessed whether there was statistically significant relationship between the economic performance and technical performance of the installed milling plants. A

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24APR2202

95% confidence interval was employed with a significance level test of (0.005).There were (40) valid cases for the chi-square test of independence. The 40 valid cases corresponded to the valid responses recorded.

Table 3 Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	178.966[a]	110	.000
Likelihood Ratio	112.526	110	.415
Linear-by-Linear Association	2.950	1	.086
N of Valid Cases	40		

The chi-square results in table (3) showed that the chi-square statistic is (178.966) and the P-value is (0.000). Therefore, at a significance level of (0.005), we conclude that the association between technical assessment and economic benefits of the installed milling plants is statistically significant.

V. DISCUSSION OF FINDINGS

The general objective of this study was to establish the technical and economic performance of selected solar milling plant units installed by the Zambia Cooperative Federation in Zambia. To achieve the general objective, benchmarking observations were carried out at the 12 sites in Solwezi, Kapiri Mposhi, Masaiti, and Chikankata districts where the solar milling plants were installed. Further semi-structured questionnaires were distributed to the cooperative leaders, solar milling plant operators, and community members from all 12 sites in the four districts highlighted above.

With regards to the technical performance of the installed solar milling plants in the 12 sites of Solwezi, Masaiti, Chikankata, and Kapiri Mposhi, the benchmarking observations carried out showed that the operational time for the solar milling plants was only above the standard operating time (8 hours) in site 3 of Solwezi and sites 4 and 5 in Masaiti District. The remaining 9 sites from Kapiri Mposhi, Chikankata, and partly Masaiti and Solwezi had the operating time of the solar milling plants below the standard operating time. The obtained results from the benchmarking observations on the operation time of the solar milling plants were in sync with the views of the solar milling plant operators, who were of the perception that the hours of operation of the solar milling plants were 6 hours.

The substandard operating time for the solar milling plants at the 12 sites above may have affected their grain milled per day, with a capacity ranging from 300 kg to 400 kg, which was below the capacity of the three sites, which were operating under a standby time of 8 hours and recorded maize grilled per day ranging from 500 kg to 540 kg.

The observed dismal operation time for the 9 sites that were operating below the standard (8 hours) could be attributed to the breakdown of the solar milling plants and the limited availability of spare parts, as attributed by the solar milling plant operators from these sites who took part in the study.

With regards to the economic efficiency or performance of the installed solar milling plants, there was a need for the milling plants to produce maximum social benefits at a low production cost. The generated results, as given by the respondents, showed that (K1, 500–K2, 500) was spent on the spare parts of the milling plants. The generated results also showed that K350–450k was generated by the milling plants in a week as revenue. This implies that in a month, taking the maximum (450), about K1,800 was generated from the sale of maize by the milling plant. Further, the revenue generated from the sale of byproducts of maize (K30k/25kg) weekly was less than the revenue realized from the sale of maize and would not increase the revenue significantly. This scenario shows that the production cost, which is for direct and indirect costs such as salaries of operators (K1, 500–K2, 500) and maintenance (K1,000–K2,500) costs associated with spare parts for the milling plants, was likely to be more than the social benefit of increased supply of maize to the community through the local market, revenue generated by the cooperatives for administrative expenses, and repayment of the loan for the project that brought about the installation of the solar milling plants.

The poor economic performance or efficiency of the installed solar milling plants with regards to generating socio-economic benefits greater than the cost of production could be attributed to the technical inefficiencies of the installed milling plants, such as the poor operation time observed in most of the sites where the milling plants were installed, which may have affected the daily production capacity of the milling plants. The other compounding factor could be attributed to the long distance between the location of the milling plants and the community markets, which may have prevented the communities from having to come to buy from the cooperatives directly in cases where the maize grains were not supplied on time and in larger quantities.

The influence of the technical performance on the economic benefits of the milling plants has been supported by the chi-square results generated by this study, which showed that there was a statistically significant relationship ($P = 0.000$, $P < 0.005$) between the technical performance and the economic performance of the installed solar milling plants.

A. *Achievement of Specific Objectives*

This section of the chapter looks at how each of the four specific objectives of this study where achieved.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24APR2202

- *Research Objective 1: To Establish the Technical Operational Characteristics of the Installed SMP*

To achieve this specific objective, benchmarking field observations and administering of semi-structured questionnaires was conducted. The results generated through the benchmarking observations revealed the following about the operational characteristics of the installed SMP

- *Power Capacity (kW) and SMP Operational Time*

Each of the twelve sites across Solwezi, Masaiti, Kapiri Mposhi, and Chikankata Districts had a consistent power range needed for operation, ranging from 7.5 kW to 9.0 kW. Nevertheless, the operational time differed across these sites. Only Site 3 in Solwezi and Sites 4 and 5 in Masaiti Districts strictly followed the standard operation time of 8 hours. On the other hand, the other nine sites, such as Chikankata, Kapiri Mposhi, and sections of Solwezi and Masaiti, functioned for less than the usual 8 hours, with a time frame ranging from 5.5 to 7 hours.

- *As Gathered from Field Observations and Surveys, the Solar Milling Plant Consists of Three Essential Components.*

- *Solar Panel Station:*

This station generates the energy required to power the milling machine.

- *Control Room:*

Housing switches and capacitors, the control room acts as the energy hub, temporarily storing and regulating energy flow to the Solar Hummer Mill (SHM). Capacitors are crucial for handling short-term fluctuations in solar energy and high-power spikes, which help maintain voltage stability.

- *Solar Hummer Mill:*

Equipped with a switch, the solar hammer mill allows users to manage its operation by turning it on and off.

Typically, the operational timeline for the solar milling plants is from 08:00 to 17:00, relying completely on solar energy for milling maize, as per data collected from field questionnaires. The solar milling plants assessed in this study are classified as first-generation solar hammer mills.

- *Configuration of a Solar Milling Plant:*

These solar milling plants, known as first-generation Solar Hummer Mills (SHMs), come with a 15.3 kW power system that is smoothly integrated with 60 polycrystalline solar panels. This setup guarantees a strong and sustainable energy source for operating the milling operations. For the system to operate sustainably, it needs 9 kW of power at maximum capacity and 7.5 kW at minimum capacity for continuous milling operations. This setup enables flexibility to adjust to different solar conditions, guaranteeing consistent operation under varying levels of sunlight intensity.

- *Operational Control and Mechanisms:*

The solar milling plant functions through a manual interface with mechanical adjustments, offering precise control over the milling process. Three strategically placed DC motors play crucial roles:

- ✓ The first motor operates the hammer mill, starting the grinding process.
- ✓ Material Transport (Second Motor): Specifically designed for material transport, the second DC motor effectively transfers milled material from the grinding chamber to the intended location.
- ✓ Extractor/Separator (Third Motor): The third motor operates as the extractor or separator, guaranteeing accuracy in the milling process by separating and gathering the milled material.

- *Integrated Control System:*

Every DC motor is intricately connected to control components. Extractors are crucial for separating and collecting the desired milled material. These components are essential for ensuring the purity of the final product by removing impurities or unwanted particles. As a control mechanism, the engaging lever helps start and stop the grinding operation. This feature guarantees accurate control in line with the production needs of the cooperative. The adjusting knob provides a customizable feature that regulates particle size during milling. This ensures versatility in milling and accommodates various preferences and requirements for the mealie meal.

- *Maximum Irradiance and Maize Milled per Day*

The generated results showed a range in maximum irradiance from 498.009W/m2 to 506.602W/m2. Site 10 under Chikankata District achieved the highest maximum irradiance at 506.602W/m2, while Site 4 under Masaiti District recorded the lowest at 498.009W/m2. The generated results also revealed a range in daily maize grains milled, varying from 300kg to 550kg. Site 4 under Masaiti exhibited the highest daily maize grains milling capacity at 550kg while Site 9 under Kapiri Mposhi had the lowest daily output at 300kg.

- *Objective 2: To Establish the Factors that Influenced the Sitting of the Plants*

From the results generated, two main factors influenced the sitting of the plants. These were proximity to the main roads of the communities and the availability of land near the FRA shades. Of these two factors, the cooperative leaders indicated that availability of land near the FRA shade was the principle factor that was considered before setting up the solar milling plants.

- *Objective 3: Determine the Economic Benefits from the Solar Milling Plants*

Generally, the economic benefit of a project is characterized by quantifiable monetary outcomes, such as income or revenue. Analysis of the results revealed that the implementation of solar milling plants led to the creation of employment opportunities. Across the 12 sites in Solwezi,

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24APR2202

Kapiri Mposhi, Chikankata, Masaiti, and Solwezi Districts, each site had two full-time solar milling plant operators earning salaries ranging from K1500 to K2,500.

Furthermore, the installation of solar milling plants resulted in an augmented supply of products to the local community market. The cooperatives were able to produce and sell byproducts derived from the processed maize, thereby increasing the revenue generated. This in turn facilitated the provision of livelihood-enhancing food commodities to the local community.

However, it is noteworthy that the revenue generated by the cooperatives did not prove to be economically significant in meeting the monthly repayment obligation of K1, 700 over the stipulated 15-year period in the loan agreement. The study findings indicated that most of the cooperatives made a minimal monthly repayment of K500. At this rate, it is estimated that it would take more than 17 years for the cooperatives to fully repay the loan, highlighting a potential discrepancy between generated revenue and the financial commitments outlined in the loan agreement. This raises concerns about the economic viability and long-term sustainability of the project in meeting its financial obligations.

- *Objective 4: Benchmark Technical Operating Conditions of the Installed SMP*

To ascertain the technical operational status of the installed Solar Milling Plants (SMP), comprehensive field observations were conducted, accompanied by the administration of questionnaires to both SMP operators and Cooperative leaders at the 12 designated sites in Solwezi, Kapiri Mposhi, Chikankata, and Masaiti. The study outcomes revealed that all 12 sites exhibited a minimum operating power capacity of 7.5kW and a maximum operating power capacity of 9.0kW.

Additionally, the study results indicated that when the installed SMPs operated at their maximum power capacity, they were capable of processing maize within the range of 100kg to 500kg. Conversely, at the minimum power capacity, the SMPs processed a quantity of maize ranging from 60kg to 100kg.

Nevertheless, the findings highlighted that a majority of the SMPs across the 12 sites deviated from the standard operational time of 8 hours, apart from Site 3 in Solwezi and Sites 4 and 5 in Masaiti District. Furthermore, it was observed that each of the 12 sites, where SMPs were installed, employed only two operators, and these milling plants encountered technical breakdowns intermittently.

- *Comparison of the Obtained Findings of the Study with Existing Empirical Literature*

The findings derived from this investigation reveal that the communities did not fully optimize the utilization of the installed Solar Milling Plants (SMPs), with most of them falling short of the standard operational duration of 8 hours. Consequently, this suboptimal operation had a direct impact on the daily processing capacity for maize. Despite this, the study demonstrated that the SMPs in Masaiti, Solwezi, Kapiri Mposhi, and Chikankata did contribute to community employment, evidenced by the engagement of operators across all 12 sites.

These results align with Munyembe's (2021) economic assessment of solar milling plants in Katete District, which indicated underperformance but a significant 40 percent contribution to job creation within the local community.

Furthermore, the study highlighted that the location of the solar milling plants in the 12 sites in Masaiti, Solwezi, Kapiri Mposhi, and Chikankata Districts was influenced by two key factors: proximity to main roads in the communities and the availability of land near Food Reserve Agency (FRA) sheds. Among these factors, the proximity to the main roads emerged as the primary determinant affecting the siting of the solar milling plants.

This observation finds support in Noorollahi et al.'s (2016) investigative study on land suitability analysis for solar farms in Iran. Their research, employing GIS and Fuzzy Analytic Hierarchy Process, identified distance to the main road as a crucial factor influencing the suitability of various regions for solar exploitation.

VI. COCLUSION AND RECOMMENDATION

A. *Conclusion*

The main objective of this study was to establish the technical and economic performance of selected Solar Milling Plant units installed by the Zambia Cooperative Federation in Zambia. In order to achieve this, the study sought to meet the following research objectives;

- *To Establish the Technical Operational Characteristics of the Installed SMPs*
- *To Establish the Factors that Influenced Siting of the Plants.*
- *To Determine the Economic Benefits from the SMPs.*
- *To Benchmark Technical Operating Conditions for the Installed SMPs*

The generated results of the study from the benchmarking observations and administered questionnaire to the research respondents showed that with regards to the operational characteristics of the installed SMPs, each of the twelve sites across Solwezi, Masaiti, Kapiri Mposhi, and Chikankata Districts had a consistent power range needed for operation, ranging from 7.5 kW to 9.0 kW. Nevertheless, the operational time differed across these sites. Only Site 3 in Solwezi and Sites 4 and 5 in Masaiti Districts strictly followed the standard operation time of 8 hours. On the other hand, the other nine sites, such as Chikankata, Kapiri Mposhi, and sections of Solwezi and Masaiti, functioned for less than the usual 8 hours, with a time frame ranging from 5.5 to 7 hours.

Further, the SMPs installed in the 12 sites exhibited a range in maximum irradiance from 498.009W/m2 to 506.602W/m2. Site 10 under Chikankata District achieved the highest maximum irradiance at 506.602W/m2, while Site 4 under Masaiti District recorded the lowest at 498.009W/m2. The generated results also revealed a range in daily maize grains milled, varying from 300kg to 550kg. Site 4 under Masaiti exhibited the highest daily maize grains milling capacity at 550kg while Site 9 under Kapiri Mposhi had the lowest daily output at 300kg

The study has also shown that the two main factors that influenced the sitting of the solar milling plants in the 12 sites across Masaiti, Solwezi, Chikankata and Kapiri Mposhi Districts were proximity to the main roads of the communities and the availability of land near the FRA shades. Of these two factors, the cooperative leaders indicated that availability of land near the FRA shade was the principle factor that was considered before setting up the solar milling plants

With regards to the economic benefits that installed SMPs brought to the community, the generated results have shown that the implementation of solar milling plants led to the creation of employment opportunities. Across the 12 sites in Solwezi, Kapiri Mposhi, Chikankata, Masaiti, and Solwezi Districts, each site had two full-time solar milling plant operators earning salaries ranging from K1500 to K2, 500.

However, it is significant to note that the revenue generated by the cooperatives did not prove to be economically significant in meeting the monthly repayment obligation of K1, 700 over the stipulated 15-year period in the loan agreement. The study findings indicated that many of the cooperatives made a minimal monthly repayment of K500. At this rate, it is estimated that it would take more than 17 years for the cooperatives to fully repay the loan, highlighting a potential discrepancy between generated revenue and the financial commitments outlined in the loan agreement.

Finally, with regards to the benchmarking of the technical operating conditions of the installed SMPs, this study gathered that all 12 sites exhibited a minimum operating power capacity of 7.5kW and a maximum operating power capacity of 9.0kW. The study also established that when the installed SMPs operated at their maximum power capacity, they were capable of processing maize within the range of 100kg to 500kg. Conversely, at the minimum power capacity, the SMPs processed a quantity of maize ranging from 60kg to 100kg.

B. Recommendations

Based on the generated on the technical and economic performance of the installed SMPs in the 12 sites of Masaiti, Solwezi, Kapiri Mposhi and Chikankata, this study recommends the following

- *Conducting Predictive, Preventive and Corrective Maintenance.*

There is need for the cooperatives to carry out regular comprehensive maintenance of the SMPs to improve their operational performance which cardinal for increased maize processing.

- *Increasing Supply of the Processed Maize Grain to the Local Market:*

There is need for the cooperatives to find ways through which they can increase the supply of their processed maize grains to the local market which is currently low and affects their revenue generation.

- *Project Management Training for the Cooperatives:*

The cooperative need training in project management as it will help them in meticulously overseeing expenditures and ensuring alignment with the loan repayment conditions for the installed milling plants.

- *Exploring Strategies to Enhance Productivity:*

The cooperatives need to diversify product offerings, or secure alternative revenue sources which may be imperative for ensuring the economic feasibility and success of the solar milling plant project. Additionally, a reevaluation of the initial financial feasibility and potential adjustments to the loan terms may be warranted to align the project with long-term economic sustainability objectives**.**

C. Areas for Future Research

This research has contributed to the research body on technical and economic performance of solar milling plants in Zambia. However, this study only focused on the technical and economic performance of the solar milling plants from the 12 sites in Masaiti, Solwezi, Kapiri Mposhi and Chikankata Districts which recently installed the milling plants. For future research, this study recommends that a comparative study be carried for solar milling plants installed in Zambia and other countries to establish whether their varying factors that influence the technical and operational performance of solar milling plants based the setting of countries.

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