NOVIA UNIVERSITY OF APPLIED SCIENCES

System performance of solar powered hammer mills in Zambia

European Project Semester: Spring Term

Date: 12/05/2023

Authors:

Linus van Nistelrooy, Nolann Bellamy and Constantin-Adrian Bălan

Project Supervisor:

Cynthia Söderbacka

In collaboration with the University of Zambia and the Copperbelt University

Content

List of figures 4

Glossary 6

1 Abstract 7

2 Introduction 8

I Research and background information 10

3 Research on Zambia 10

4 Hammer mill 16

5 Photovoltaic systems 19

5.1 Micro/mini grid 19

5.2 How a standalone PV-system works 20

5.2.1 Simplified Stand-Alone PV System 20

5.3 Solar cells 22

5.3.1 How does a solar cell work? 22

5.3.2 What is a Solar Cell? 23

5.3.3 Working principle of a solar cell 23

5.3.4 The p/n transition 25

5.3.5 Photovoltaic effect 25

5.4 Photovoltaic modules (PV modules) 26

5.4.1 Construction of PV modules 26

5.4.2 Bypass diodes 28

5.4.3 Specifications of a solar module 30

6 Inverter 34

6.1 Different inverter types 34

6.2 Power optimizers 36

6.2.1 MPP Tracking ... 36
7 Battery ... 38
7.1 Battery energy storage system ... 38
7.1.1 Why are battery energy storage system facilities important? ... 38
7.2 Battery management system ... 39
7.2.1 How does BMS work? ... 39
7.3 Storing Solar Energy ... 41
7.4 Conclusions ... 42
8 Maintenance of solar systems ... 43
8.1 Cleaning solar panels ... 43
8.2 Solar cable maintenance ... 43
9 Data logger ... 45
II Analyze and modeling ... 46
10 CASE 1: Copperbelt University ... 47
10.1 System specifications CASE1 ... 48
10.1.1 Solar PV ... 48
10.1.2 Hammermill ... 49
10.2 System configuration ... 50
10.3 Analyzes ... 52
10.3.1 Study of the system from an energy point of view ... 54
10.3.2 Study of the system from the user's point of view ... 57
10.4 Improvements ... 63
11 CASE 2: University of Zambia ... 68
11.1 System specifications CASE2 ... 69
11.1.1 Solar PV ... 69

11.1.2 Battery 70
11.1.3 Hammermill 71
11.2 System configuration 71
11.3 Analyzes 72
11.3.1 Study of the system from an energy point of view 72
11.3.2 Study of the system from the user's point of view 75
11.3.3 Householder cases: 82
12 Case 1 & case 2 : comparison 86
13 Calculations 80
III Conclusion 88
14 Conclusion and discussion 88
15 Appendix 90
15.1 Team presentation 90
15.2 Project management 91
15.2.1 Gantt chart and WBS 91
15.2.2 Belbin test 94
16 References 100

List of figures

Figure 1: Energy sector overview 8
Figure 2: Location of Zambia 10
Figure 3: Zambia Electricity Access 1990-2020........ 11
Figure 4: Access to electricity in rural and urban area from 2000-2020 in Zambia ... 12
Figure 5: Levelized cost of electricity by technology in Africa in the Sustainable Africa Scenario, 2020-2030 12
Figure 6: Sunrise, sunset, dawn and dusk times for the whole year in Lusaka (the big one) and Vaasa (the small one top) right) 13
Figure 7: Surface energy and surface meteorology in Lusaka and Vaasa 14
Figure 8: Sun path diagram in Lusaka (Zambia)........ 15
Figure 9: Picture of a hammer mill 16
Figure 10: Hammer mill dashboard 17
Figure 11: Typical meal in Zambia........ 18
Figure 12: Basic structure of a microgrid solar energy system 19
Figure 13: Standalone system with charge controller 20
Figure 14: How do solar panels work? 22
Figure 15: Composition of solar cell 23
Figure 16: Silicon crystal 24
Figure 17: Principle of conduction of electric current in a pure solid-state semiconductor 24
Figure 18: Electron transfer between n and p layer 25
Figure 19: Illustration of photovoltaic effect 25
Figure 20: Main components of a solar panel........ 26
Figure 21: 60 solar cell modules 27
Figure 22: Standard solar cells without shading 28
Figure 23: Standard solar cells affected by shadow compared with bypass diodes . 29
Figure 24: Open circuit voltage and irradiance graph 32
Figure 25: IV curve of a solar cell 32
Figure 26: Irradiation, short circuit current 33

Figure 27: Different types of inverters 34
Figure 28: Graph MPP tracking 37
Figure 29: Figure standalone system 38
Figure 30: Picture typical BMS-system 40
Figure 31: Solar storing yield 41
Figure 32: Google maps geographical photo CBU case study 47
Figure 33: Picture provided by Mr. Fumpa 48
Figure 34: Image from the manufacturer's website and Abel Fumpa 49
Figure 35: Total mass introduced in the Hammer mill 51
Figure 36:Example of mass introduced in the Hammer mill.................................... 51
Figure 37: Hammermill working area 54
Figure 38: Calculated consumption and production profile 54
Figure 39: Energy overproduction 55
Figure 40: Table of blackouts 59
Figure 41: Maximum amount of minutes the hammermill can operate 60
Figure 42: Hammermill maximum working minutes with battery.............................. 66
Figure 43: Maximum production of meal compared with system with battery........... 67
Figure 44: The days the hammermill can't work, compared with battery 67
Figure 45: Google maps geographical photo UNZA case study 68
Figure 46: Picture of the solar panel 69
Figure 47: Picture of the battery 70
Figure 48: Calculated consumption and production profile 72
Figure 49: Energy overproduction 73
Figure 50: Maximum amount of minutes the hammermill can operate 78
Figure 51: Householders consumption graph 83
Figure 52: QR code WBS 91
Figure 53: QR code Gantt diagram 92
Figure 54: Gantt diagram 92
Figure 55: Efficiency calculations of the solar system 93

Glossary

- AC: Alternating Current
- Ah: Ampere hours
- BMS: Battery Management System
- CCS: Central control system
- DC: Direct Current
- EPS: European project semester
- HM: Hammer mill
- kWh: kilo Watt hours
- MPP: Maximum Power Point
- PV: Photovoltaic system
- REA: Rural Electrification Authority
- SP: Solar panel
- SPH: Solar panel powered hammer mill
- UAS: University of applied sciences
- UNZA: University of Zambia
- WBS: Work Breakdown Structure
- Wp: Watt peak
- ZMK: Zambian Kwacha (national unit of currency)

1 Abstract

Two case studies of solar panel hammer mills from Zambia, Africa are analyzed in this paper. The first case is from Copperbelt University where they don't use batteries for energy storage. And the second case is from the University of Zambia where they use batteries for energy storage with a capacity of 26 kWh. While we have focused on only two study cases, there are more than 2000 installations in Zambia that are like the ones studied.

Hammer mills were the perfect solution to the problems of grain processing in rural areas of Africa where there is no electricity. The hammer mill is used to produce mealie meal, a powder made from maize grain that is used to make the staple food called Nshima (a very thick porridge eaten by hand). It's very important for the local people in Zambia because it gives them energy to carry on with normal activities, which include farming and other labor-intensive activities.

The objective of this report is to analyze & evaluate the efficiency of the current system set-up and identify areas for improvement such as the operating hours of the hammer mills. The results were obtained using SAM - System Advisor Model. This software was used to simulate the operating model of the hammer mill for 3 years using photovoltaic panels with and without batteries. We were able to find the best possible way to use the system with and without batteries to produce the maximum amount of meal and what's the best periods to use the hammer mill.

With all the data processed by SAM software, Microsoft Excel is used to analyze the solar production of energy and the number of shortages during the 3 years. In the final output it’s a comparison between our 2 cases to evaluate how many minutes per day during the year the system can produce maze.

2 Introduction

Zambia's energy sector consists of many different types of energy sources. The largest industry is the copper industry, of course the energy sector depends on this industry. There have been some significant changes in recent decades. The government has transformed the privatized industry into an open market economy. This has led to a 6% growth in the period from 2005 to 2013 (ZambiaInvest, n.d.).

The energy sector comprises three subsectors, namely: Electricity, Petroleum and Renewable Energy. Today, the largest source of energy in Zambia is wood fuel, e.g., firewood and charcoal (Mbumba, 2023). As shown in Figure 1, only 14% of the total energy produced is based on electricity.

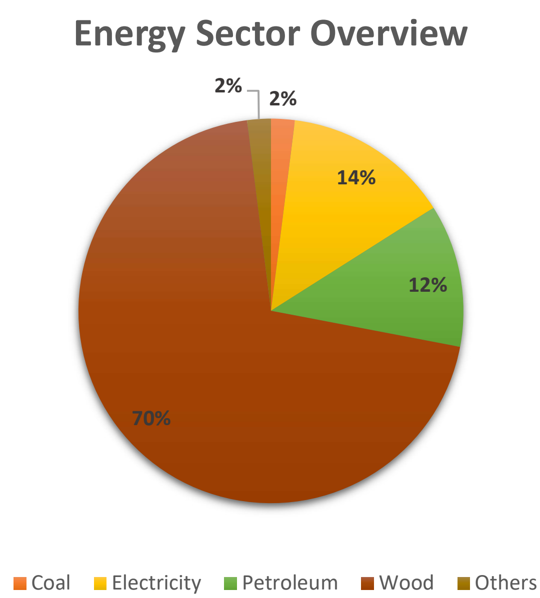


Figure 1: Energy sector overview

Mining consumes over 50% of the country's output and is the largest consumer of electricity. This is not surprising considering that Zambia's primary energy plan was designed with the mining industry of the Copperbelt Province in mind. It is estimated that urban centers consume 48% of electricity, while rural areas consume only 2%. 25% of the population generally has access to electricity (Mulozi, 2008).

Zambia's national grid is still inaccessible to a significant portion of the rural population. This problem led to the creation of the Rural Electrification Authority in 2003. The new legislation identifies grid expansion and solar installation as two key initiatives to increase access to electricity in rural areas (*Rural Electrification Act 2003 – Policies*, 2018).

This project was partly realized in collaboration with the Rural Electrification Authority. But it's mainly part of the European Project Semester (EPS) program at Novia University of Applied Science. "Novia's area of operation is along the Swedish-speaking coast, and the university operates in Turku, Raasepori, Pietarsaari, and in Vaasa, where the EPS is delivered. With 4500 students and about 320 employees, the university is the largest Swedish-speaking university of applied sciences in Finland." (Novia UAS Website, n.d.)

The stakeholders for this project are team coach, Cynthia Söderbacka from Novia UAS (project leader), the University of Zambia School, the Copperbelt University in Zambia, the Rural Electrification Authority of Zambia, and the Zambian Farmers Union.

I Research and background information

3 Research on Zambia

Zambia (the Republic of Zambia) is vast territory of 752,617 km2, approximatively 25 times the size of Belgium's territory, with almost 20 million inhabitants in 2023. Concentrated mainly around Lusaka in the south and the Copperbelt Province to the north, the core economic hubs of the country (“Zambia,” 2023). This is the reason for the heterogeneous distribution of the population in the country and partly explains the difficulties in developing an electrical network throughout the country. Places with large populations (such as the capital, Lusaka) have easier access to electricity.

Figure 2: Location of Zambia

Another aspect that can explain in other parts the difficulties in developing easy access to electricity is the economic aspect:

“The overlapping crises (covid, Russian invasion, climatic) are affecting many parts of Africa’s energy systems, including reversing positive trends in improving access to modern energy (electricity), with 4% more people living without electricity in 2021 than in 2019. They are also deepening the financial difficulties of utilities, increasing the risks of blackouts and rationing. They slow down the electricity access development.” (IEA, 2022)

Access to electricity is also associated with health risks (e.g. clean cooking is problematic), making it even more important to find an efficient solution. This is not an easy task, as providing universal access to affordable electricity means connecting more than 10 million people in Zambia.

In fact, access to electricity should be viewed as the percentage of the population with access to electricity. Zambia's access to electricity for 2020 was 44.52%, an increase of 1.52% from 2019.

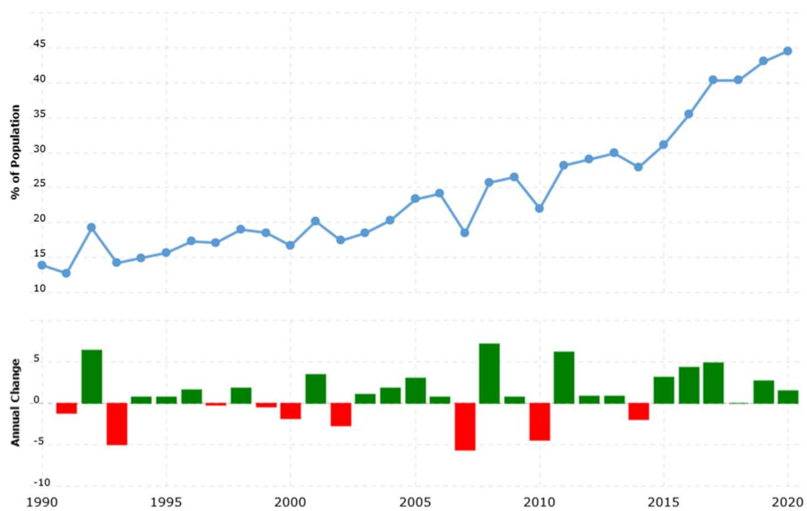
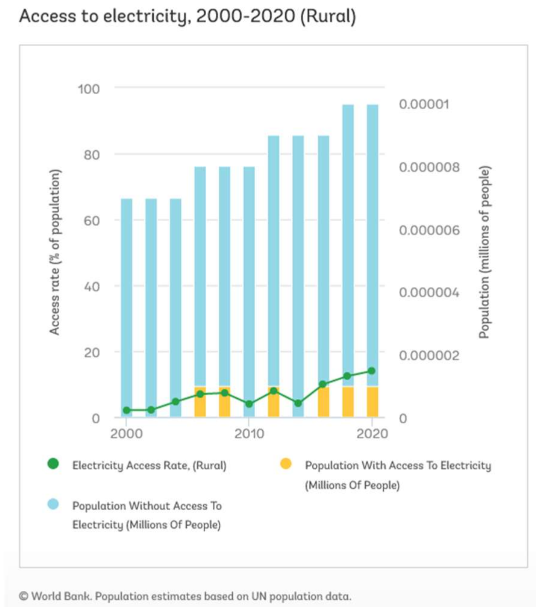


Figure 3: Zambia Electricity Access 1990-2020

According to the Figure 3 the evolution of electrification in Zambia is more and more important (acceleration [2000 – 2005] increase of 7% versus [2015-2020] increase of 15%) (*Zambia Electricity Access 1990-2023*, n.d.). ”But in fact, the rate of electrification in rural areas is slower” (energyaccess-africa, 2017)



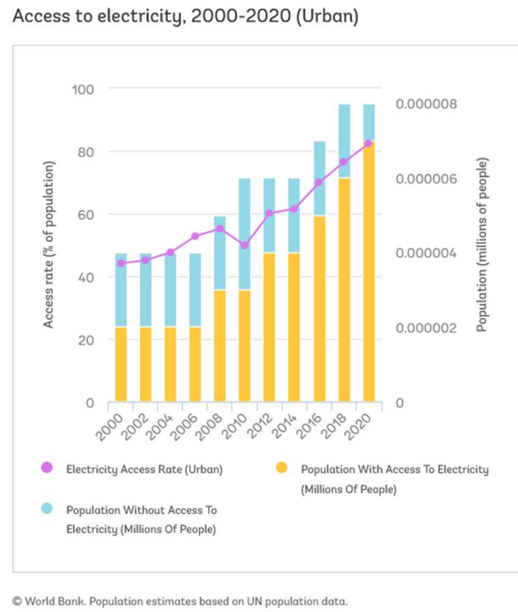


Figure 4: Access to electricity in rural and urban area from 2000-2020 in Zambia

The comparison between the rural and urban areas in Figure 4 shows a significant difference in terms of access to electricity. While electricity access in urban areas reaches 82% in 2020, it is only 14% in the same year. The evolution curve also shows that urban areas develop faster than rural areas. The data for 2021 is missing, de facto it is not possible to see here the results of the previously mentioned crisis in electrification.

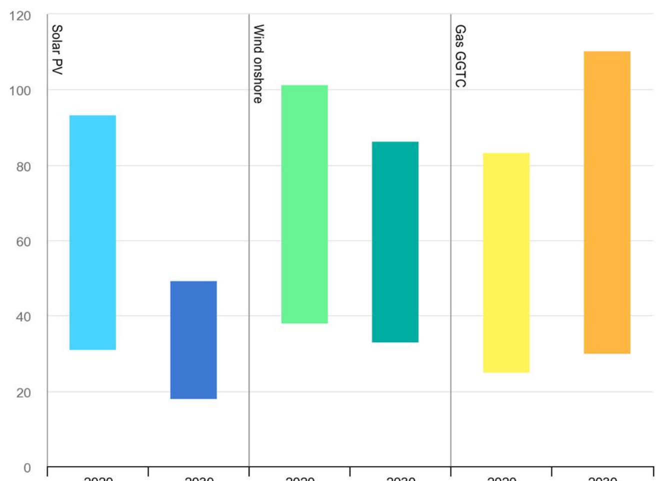


Figure 5: Levelized cost of electricity by technology in Africa in the Sustainable Africa Scenario, 2020-2030

According to the graph[1] in Figure 5, solar panels are the most profitable solution compared to onshore wind and gas GGTC (graph error: CCGT = Combined Cycle Gas Turbine). Thus, the improvement of the two systems studied can contribute to a sustainable improvement of the way of life in Africa. This solution is partly explained by the huge solar potential: Africa has 60% of the world's best solar resources, but only 1% of solar PV capacity is installed. Solar PV is already the cheapest source of electricity in many parts of Africa (IEA, 2022).

To get an idea of the solar potential, we will compare Vaasa (a city in Finland) with Lusaka (capital of Zambia).

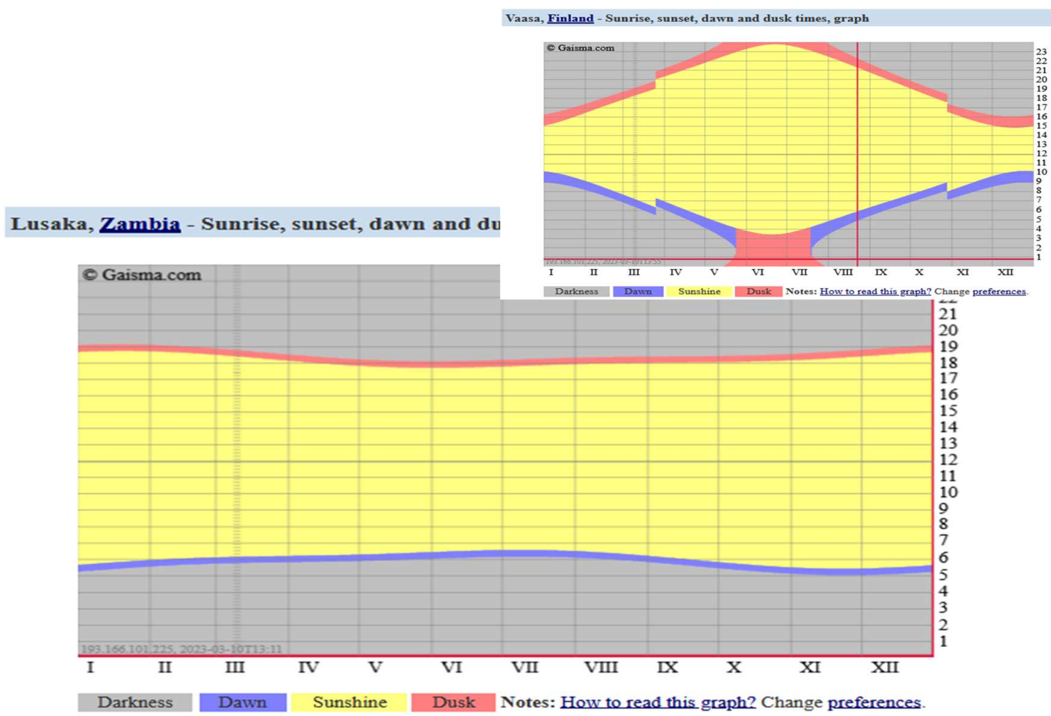


Figure 6: Sunrise, sunset, dawn and dusk times for the whole year in Lusaka (the big one) and Vaasa (the small one top)

As we can see on the graph[2] Figure *6* (Lusaka), the geographic location of Zambia allows them to have a daylight period that lasts almost the entire year. This daylight period is between 12 and 14 hours. As a result, the solar energy production can be

[1] Note: Additional link for data https://datatopics.worldbank.org/world-development-indicators/

[2] Question about graphs https://www.gaisma.com/en/info/help.html

guaranteed during half a day, which makes it a more feasible solution (in terms of electricity production) than in Vaasa, where the variation of the light-day period causes important limitations to the solar production in winter with only 5 hours of light and 20 hours in summer, which can cause new problems.

Lusaka, Zambia - Solar energy and surface meteorology

Variable	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Insolation, kWh/m²/day	5.19	5.27	5.34	5.37	5.13	4.83	5.03	5.77	6.50	6.51	5.92	5.25
Clearness, 0 - 1	0.46	0.48	0.52	0.59	0.64	0.65	0.65	0.67	0.67	0.61	0.53	0.47
Temperature, °C	21.96	22.00	21.71	21.38	20.15	18.31	18.54	21.35	25.29	26.20	24.27	22.25
Wind speed, m/s	4.02	3.93	3.81	4.09	3.93	4.11	4.33	4.69	5.40	5.28	4.89	4.43
Precipitation, mm	216	180	85	30	4	0	0	0	1	16	90	199
Wet days, d	17.2	16.1	9.9	2.7	0.0	0.0	0.0	0.0	0.0	2.1	8.5	16.8

These data were obtained from the NASA Langley Research Center Atmospheric Science Data Center; New et al. 2002

Vaasa, Finland - Solar energy and surface meteorology

Variable	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Insolation, kWh/m²/day	0.13	0.70	1.81	3.69	5.28	5.91	5.43	4.03	2.42	0.99	0.29	0.05
Clearness, 0 - 1	0.25	0.39	0.43	0.51	0.53	0.52	0.51	0.48	0.45	0.37	0.34	0.20
Temperature, °C	-7.01	-7.92	-4.27	0.71	7.16	12.37	15.42	14.39	10.09	5.09	-0.32	-4.10
Wind speed, m/s	7.29	6.98	6.59	6.31	6.11	5.92	5.82	6.01	6.67	7.32	7.31	7.31
Precipitation, mm	33	24	26	26	32	37	53	62	61	51	50	39
Wet days, d	20.8	15.4	13.7	12.4	10.7	10.7	12.5	14.5	16.1	16.4	19.1	19.2

These data were obtained from the NASA Langley Research Center Atmospheric Science Data Center; New et al. 2002

Figure 7: Surface energy and surface meteorology in Lusaka and Vaasa

Another important criterion is solar irradiation; in fact, electric PV production depends directly on this irradiation. In relation to the observations made previously about short light days during winter, combined with the observation of low irradiation power in Vaasa (Figure 7), using a PV system is almost useless during the winter in this city. For Zambia, irradiation appears to be almost constant, with a minimum of 4.83 kWh/m²/day and a maximum of 6.51 kWh/m²/day Figure 7. However, cloud cover (0 = very cloudy and 1 = sunny) can have a significant impact on PV production. Despite these observations, the meteorological conditions in Zambia remain favorable.

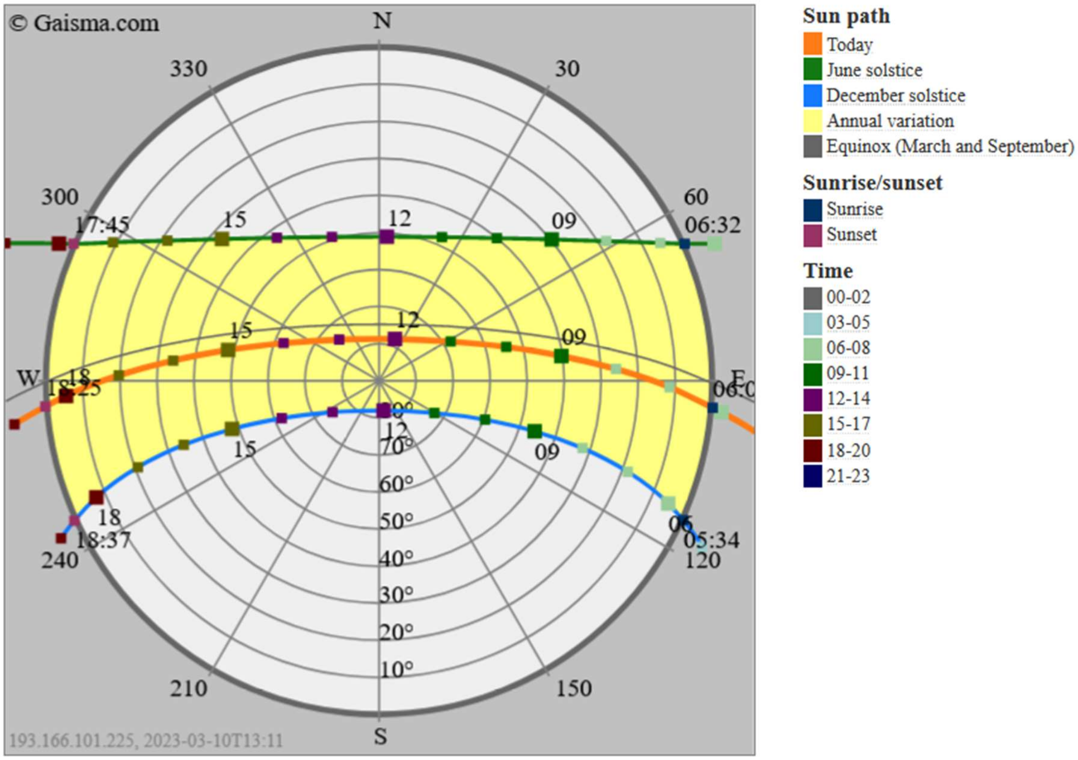


Figure 8: Sun path diagram in Lusaka (Zambia)

The Zambian solar (in terms of inclination (a 50° interval) and rotation (globally straight orbit)) makes it easy to "track the sun" with solar panels based on Figure 8 (Lusaka, Zambia - Sunrise, Sunset, Dawn and Dusk Times for the Whole Year, n.d.).

Information about habits (and changes during the rainy season are missing, it is necessary to interview local people). However, the following information was found: “The rains are mostly short showers, often in the late afternoon and rarely constant. The night sky can be interrupted by lightning and roaring thunder among the sounds of the flora and fauna, but as the sun comes up, the clouds disperse and behold, a crystal-clear day!” (Zambia Rainy Season, n.d.).

4 Hammer mill

To solve the problems of grain processing in rural areas where there is no electricity, the hammermills were the perfect solution. That's why they designed 2000 new sets of solar power mills for this case. Based on the actual situation in Africa, the system is a micro-off-grid power generation system that will provide steady converted DC power support for the device through the controller and DC/DC from solar power generation. The technique fundamentally solves the equipment's power problems and represents a significant advancement over raw manual labor for automated processing in the food processing sector (Shandong Dejian Group Co., Ltd., n.d.).

Figure 9: Picture of a hammer mill

The hammer mill is used to produce mealie meal, a powder made from maize grain used to make the staple food called Nshima (a very thick porridge eaten by hands). It’s very important for locals for Zambia because it give them energy to carry with the normal activities that include farming and other labor intense activities. This hammer mill can produce up to 1500kg per day and the price of 25kg bag of maize cost K150.

Figure 10: Hammer mill dashboard

The hammer mill has made a great contribution to the people of this village. The use of this machine in the same village where the people live and not very far away is a great advantage for everyone who wastes a lot of time traveling 10 km in dry weather to get a bag of maze meal.

All communities in Zambia that are concerned about food insecurity will benefit greatly from these solutions. In many rural areas of Africa, people rely on subsistence agriculture to feed themselves and their families. These cultures can use the hammer mill to turn maize into maze meal, which can then be used to make a variety of staple foods.

A hammer mill can be used to produce maze meal for communal use and food for individual consumption. Farmers can use the refined corn to create value-added goods or sell them to nearby marketplaces. This installation helps increase the nutritional value of food consumed by individuals in rural areas. It can also help combat malnutrition and other health problems that are prevalent in much of Africa.

Figure 11: Typical meal in Zambia

In addition, hammer mills can make life easier for communities in Africa in several ways: Time-consuming, traditional methods of processing maze meal, including the use of pestles or grinding stones, can be labor-intensive and time-consuming. By saving time and effort, a hammer mill allows community members to spend more time on things like health care, education, and employment. It also provides access to technology; a hammer mill can give a rural community access to modern technology that they may not have had before. This can promote both social and economic development by bridging the technological gap between rural and urban areas.

Finally, it can also help communities feel more empowered by giving them more control over their food supply and financial future. Instead of relying on other sources for food or cash, they can process their own hammermill and sell the goods locally. And, as mentioned earlier, a hammer mill can help improve the nutritional quality of the food consumed by the community. This can have a positive impact on the health and well-being of community members, especially children and vulnerable groups.

5 Photovoltaic systems

5.1 Micro/mini grid

A micro/mini grid, off grid photovoltaic system or stand-alone PV grid supplies power to an electrical application that is not connected to the grid. Typically, the PV modules charge a battery as energy storage that provides a buffer between the fluctuating PV power and the consumer (Durão et al., 2020). Mini grid systems can supply either direct or alternating current supply. In rural areas are these autonomous systems the most common.

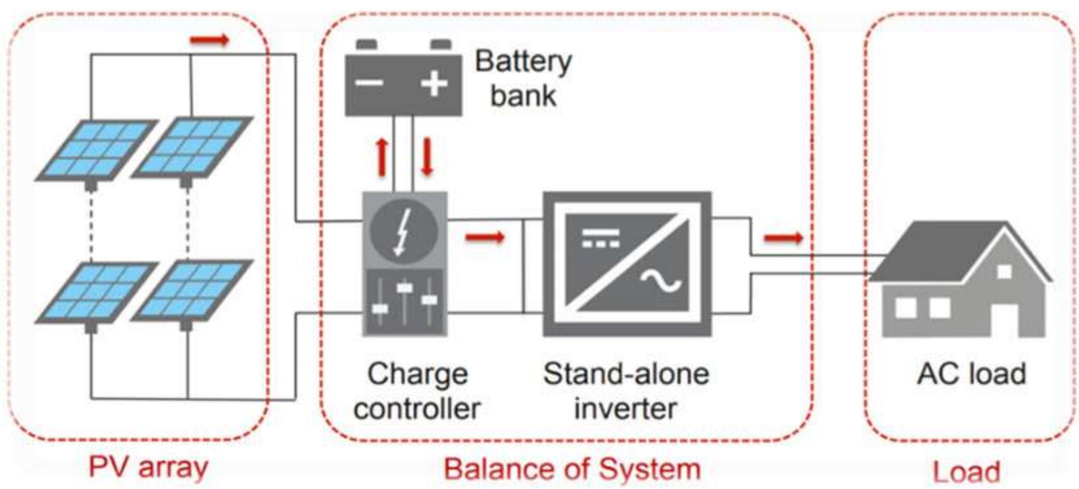


Figure 12: Basic structure of a microgrid solar energy system

An off-grid solar electric system is one that relies primarily on solar energy as its primary source of power. There are many places on earth where there is no access to electricity of any kind. An off-grid solar electric system can be the best source of electricity in certain areas. The fact that this system is independent of the grid and other sources of electricity is the best advantage.

It is called an off-grid photovoltaic system because it has no connection to the grid or any other source of electricity. As the only source of energy in this system, the sun had to have a way of continuing to work at night. The solution is a battery storage system. A stand-alone solar system must therefore include a battery storage system. However, if the system is only intended for a load that is used during the day, the battery system can usually be excluded from the system (Electrical4U, 2020).

5.2 How a standalone PV-system works

Simple stand-alone PV systems automatically generate electricity to charge battery banks during the day for use at night when the sun's energy is not available. Rechargeable batteries are used in small stand-alone PV systems to store electricity generated by solar panels or an array.

When conventional power sources are either impractical or unavailable to provide electricity for lighting, appliances and other uses, off-grid PV systems are the best option for remote rural locations and applications. In these circumstances, it is more feasible to install a single stand-alone PV system than to pay the local electricity company to run power lines and cables directly to the home as part of a grid-connected PV system (Altenenergytutorials, 2023).

5.2.1 Simplified Stand-Alone PV System

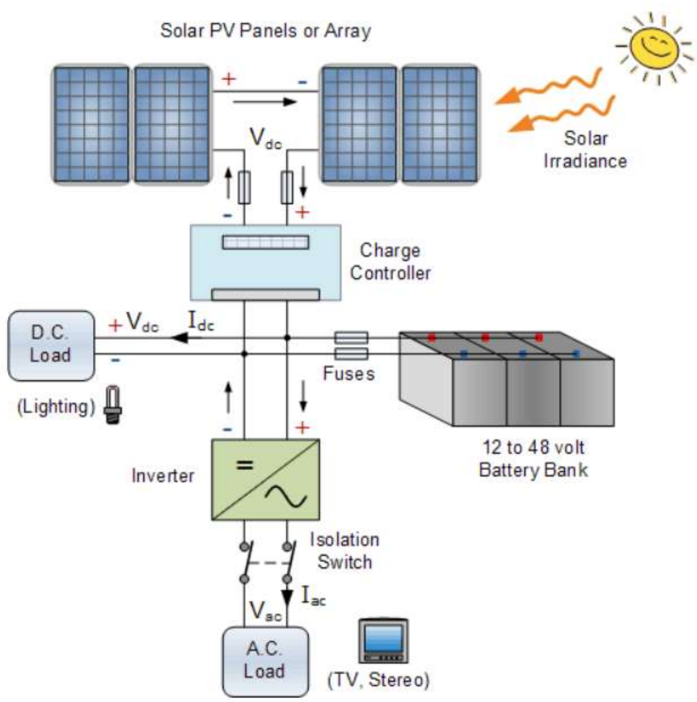


Figure 13: Standalone system with charge controller

Although the solar array is a significant part and expense of a stand-alone PV system, other parts are frequently required (Altenenergytutorials, 2023):

- Batteries - Batteries are an essential part of any standalone PV system, while they may be optional depending on the design. For use at night or in emergencies during the day, batteries are used to store the electricity generated by solar panels. Battery banks can be 12V, 24V, or 48V and have a total amperage of many hundreds of amps, depending on how the solar array is set up.
- Charge Controller - By dissipating surplus power into a load resistance, a charge controller regulates and controls the output from the solar array to prevent the batteries from being overcharged (or over discharged). Although charge controllers are not required in a standalone PV system, it is a good idea to include one for security purposes.
- Fuses and Isolation Switches - These enable PV installations to be safeguarded against unintentional wire shorting by enabling power from the PV modules and system to be turned "OFF" when not necessary, conserving energy and extending battery life.
- Inverter: An additional possible component in a stand-alone system is the inverter. For usage in the home to power AC mains equipment like TVs, washing machines, refrigerators, etc., inverters transform the 12V, 24V, or 48V direct current (DC) power from the solar array and batteries into an alternating current (AC) electricity and power of either 120 AC or 240 AC.
- The electrical wiring is the last element needed for a PV solar system. The cables must be properly rated for the required voltage and power. Bell or telephone cable that is too thin won't work.

5.3 Solar cells

5.3.1 How does a solar cell work?

In a photovoltaic solar cell, light is converted directly into electricity (without any chemical or mechanical process). A solar cell is composed of up of a thin film of semiconducting material that conducts electricity efficiently when it is exposed to light. The most used material is pure silicon, which is given a negative top layer and a positive bottom layer by chemical side effects, like a battery's "minus" and "plus." Solar cells have no moving parts, consequently they are not subject to wear and tear and the theoretical lifetime is unlimited.

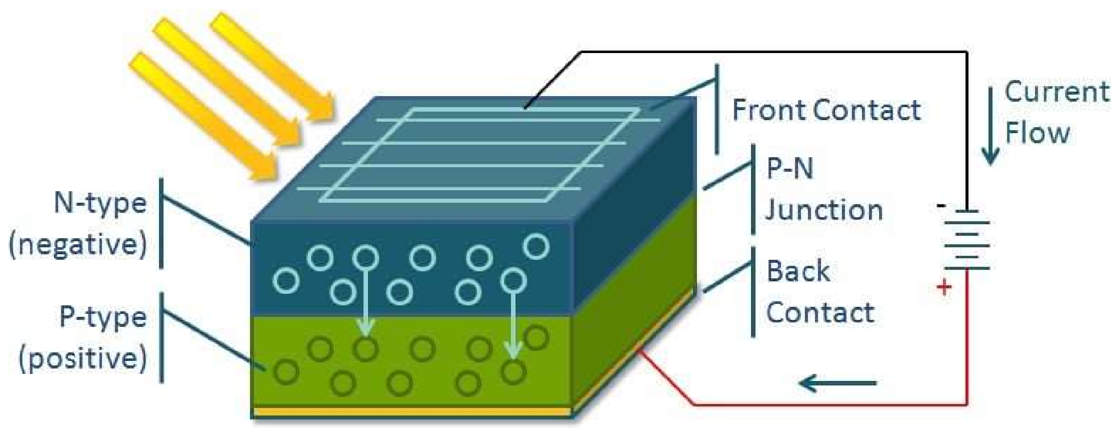


Figure 14: How do solar panels work?

Solar cells mainly use the visible part of sunlight (200-1200nm). Per type of solar cell, only one part of the light spectrum (color) will be utilized. This can possibly be solved by combining different semiconductors in different layers so that different colors of the light spectrum can be utilized. Obviously, not all incoming light will be converted either, some will be reflected, and another part converted into heat (~55%). These are the main losses that occur in PV systems. The maximum efficiency we can get from silicon cells is 45% (Verelst, 2021).

5.3.2 What is a Solar Cell?

Solar cells are semiconductors that become electrically conductive when exposed to light. In Figure *15* is the composition of a solar cell.

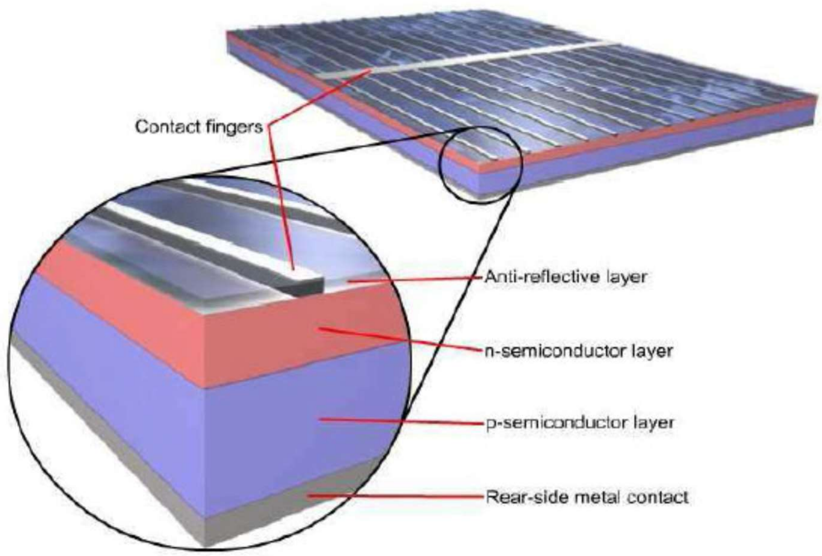


Figure 15: Composition of solar cell

5.3.3 Working principle of a solar cell

Solar cells are made of Silicon, the second most abundant element in the Earth's crust. A silicon atom has 4 valence electrons (electrons in a not yet filled electron shell). In a silicon crystal, electrons from 2 neighboring atoms form a pair. In this state, the crystal is not conductive since there are no free electrons to move charge. When light falls on the crystal, this light energy is absorbed by electrons. Once an electron pair has absorbed enough energy, it breaks apart and the electrons can move freely. Each electron that moves leaves a "hole" at its original position. The silicon becomes conductive. If the energy supply drops, then each drifting electron will release its energy back and return to a free "hole".

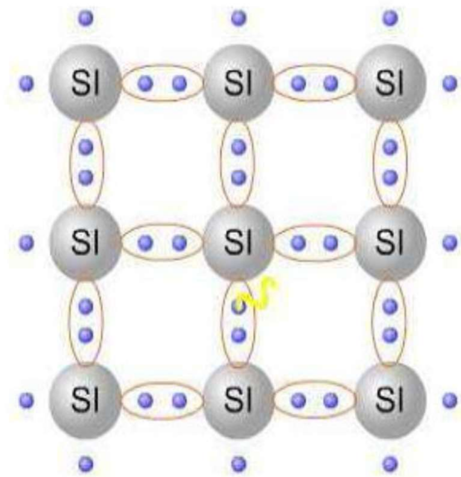


Figure 16: Silicon crystal

An electric field can be used to separate electrons from holes. Impure atoms allow an electric field to be generated in a semiconductor. For this we are going to add atoms with 5 electrons. As a result, we get n-doped material, which is slightly negative in charge.

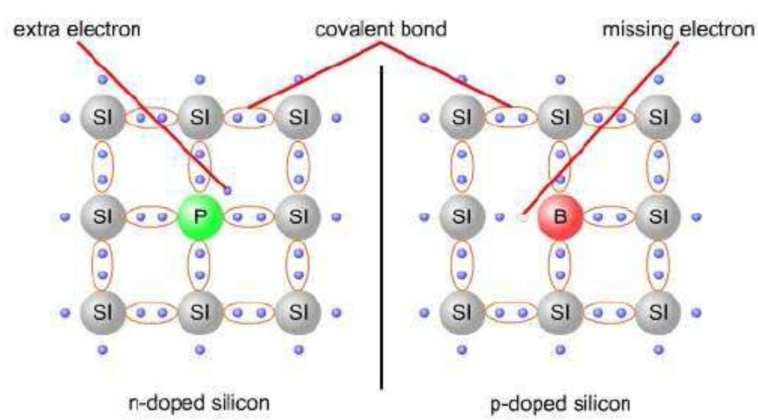


Figure 17: Principle of conduction of electric current in a pure solid-state semiconductor

Atoms with 3 electrons are introduced into the p-doped material. This becomes slightly positive in charge. If we now bring these 2 layers side by side, an electric field will be created in this p/n transition.

5.3.4 The p/n transition

Electrons from the n-layer want to go to the holes in the p-layer

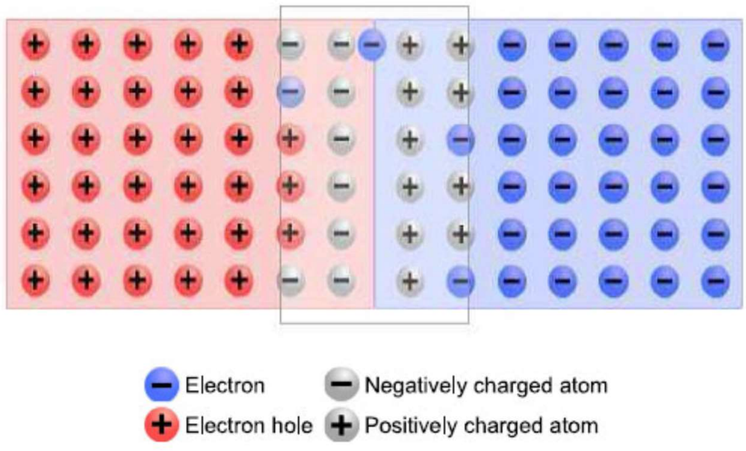


Figure 18: Electron transfer between n and p layer

As electrons leave the n-layer, the atoms that remain behind will become slightly positive in charge become positive. In contrast, in the p-layer where the incoming electrons combine with a "hole" the charge becomes slightly negative.

5.3.5 Photovoltaic effect

When light strikes the PV cell, the atoms are "activated" to form electron/hole combinations. If this happens outside the P/N transition, the electrons/holes combine very quickly. Inside the P/N junction (transition), the electrons/holes are separated by the local electric field. The resulting electrons want to go to the n-layer, while the holes want to go to the p-layer. If a consumer is connected, a current will flow.

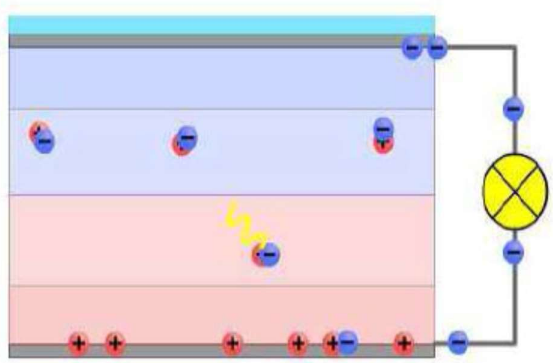


Figure 19: Illustration of photovoltaic effect

5.4 Photovoltaic modules (PV modules)

Individual solar cells cannot be used in practice, they generate a low voltage, they are fragile, and the metal contacts are susceptible to moisture. Therefore, solar cells are interconnected via soldered strips and placed together in a so-called photovoltaic module. An additional advantage of building the solar cells together in a module is better handling and easier assembly (Flemish Energy Agency, 2013).

5.4.1 Construction of PV modules

A light-transmitting sheet, usually composed of glass, but which can also be made of polycarbonate film (which can become yellow over time when exposed to light), makes up the front of photovoltaic modules. To allow as much light as possible, the glass is low in iron and thermally tempered. It is resistant to water, vapor, scratches, hail, and it self-cleans when it rains. Watertightness, vapor density, and thermal conductivity are significant factors for the reverse side (De Winne, 2012).

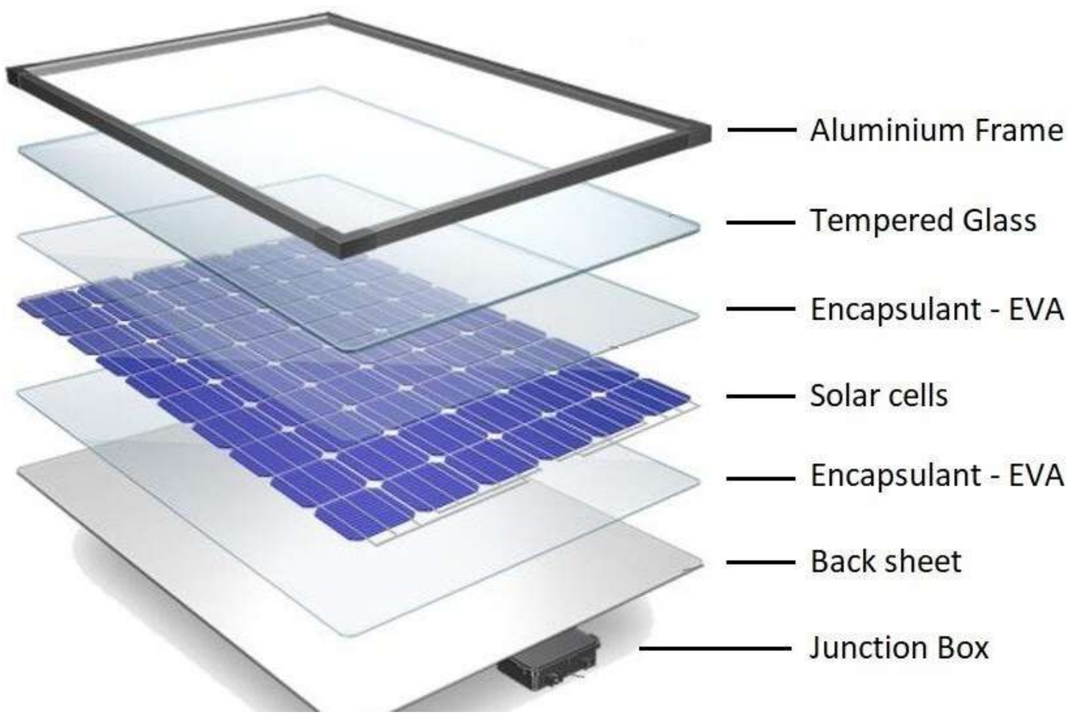


Figure 20: Main components of a solar panel

As can be seen in Figure 20, the solar cells are wedged between the front and back and protected from the elements by being encased in moisture-resistant plastic, most commonly ethylene vinyl acetate (EVA). This is because the metal connections on and between the cells can be affected by moisture. In addition, the encapsulant must be able to withstand high temperatures, temperature fluctuations, and UV radiation (Svarc, 2020). The module is typically surrounded by an aluminum frame for strength and ease of mounting on a support structure. A weatherproof junction box is attached to the back of the module for electrical connections to other PV modules or to the inverter.

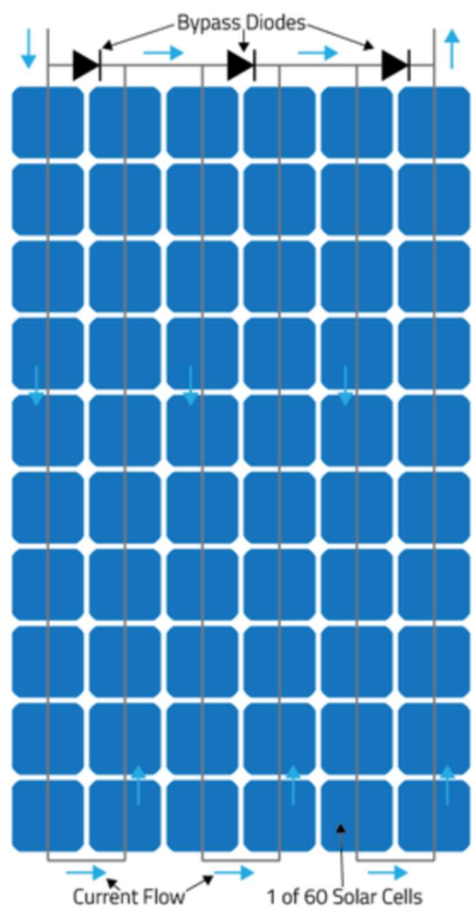


Figure 21: 60 solar cell modules

Depending on the cell type used, most common modules have 60 cells that are connected in series by bus bars to generate a voltage of 30 to 40 volts. Current can move through all of the cells in a circuit because to the electrical contacts known as bus bars connecting the cells (Positronic Solar, 2019). There are 3 interconnected substrings, as shown in Figure 21. Each substring consists of 20 cells. As additional strings are added to the panel, the voltage will increase while the current will remain the same. After extensive research, it appears that the solar panels for the case studies are made up of 60 cells (ENF Ltd., n.d.).

5.4.2 Bypass diodes

The bypass diodes ensure that the panel's output is not completely lost if one or more solar cells in a pair of strings become shaded or dirty. Sand on the solar panels can also exacerbate this problem. A shaded cell for example heats up because of the current flowing through the other cells. This cell then becomes a resistor instead of an energy producer. This energy consuming cell is called a hot spot. The bypass diodes prevent the lower current producing cells from lowering the current of all the cells (Positronic Solar, 2019). As a result, the efficiency of the module may decrease over time, or the solar panels may be severely damaged if bypass diodes are not installed.

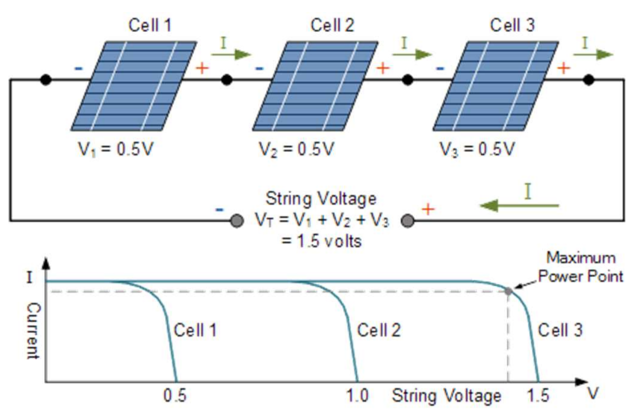


Figure 22: Standard solar cells without shading

As shown in Figure 22, this is the standard connection between the solar cells. If there is a problem such as shading and/or dust on the cells. This will reduce the current of the entire connected module and string. As a result, there will also be an effect on the maximum power production of the whole solar system due to this problem as shown in Figure 23. The power output decreases disproportionately due to partial shading. In some situations, shading 10% of a solar panel can reduce its power output to 0 watts.

For example, shading the bottom six solar cells of a normal 60-cell solar panel can result in a 100% reduction in power output (Anasjonahidrissi, 2021).

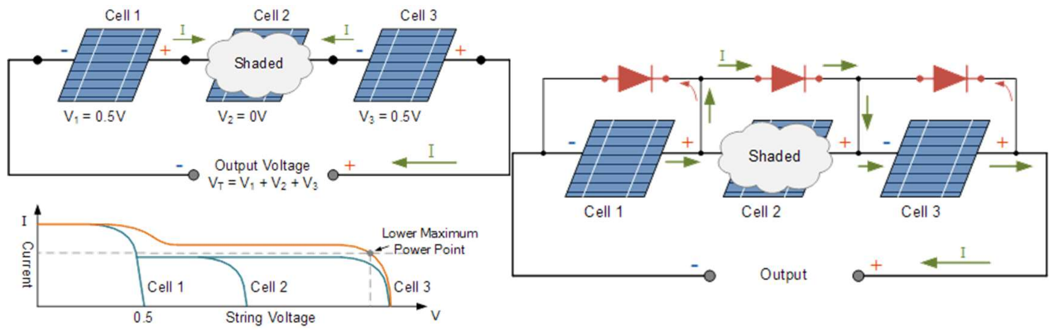


Figure 23: Standard solar cells affected by shadow compared with bypass diodes

The solution to avoid this problem, as mentioned earlier, is to use bypass diodes. A diode is an electrical component made to only allow one direction of electric current to flow. Each of its two ends has an electrode with a separate charge. In contrast to the negatively charged "cathode" end, the "anode" end has a positive charge. Natural current always moves from the anode to the cathode (Christensson, 2016). When the solar cells generate electricity, the current will pass through the solar cells. The moment solar cell 2 in Figure 23 is shaded, most of the current will pass through the diode instead.

It can be concluded that solar panels with bypass diodes not only avoid hot spots, which can prevent fires and malfunctions in the panels. But it could also improve the overall efficiency of solar systems.

5.4.3 Specifications of a solar module

Solar panels have many different specifications. To get an idea of the system performance, some background information about the panels is necessary. A more in-depth look at the practical data can be found in heading 8.1 System specifications CASE1 and heading 9 System specifications CASE2.

5.4.3.1 Watt Peak

To explain what means a watt peak it's necessary to understand first the concept of kWh. So, an electrical device or generator's power is measured in Kilowatts (kW). The quantity of electrical energy utilized by an electrical device or generated by an electrical generator is measured in Kilowatt hours (kWh). The quantity of electrical energy used or generated by a device or generator per unit of time is measured in kWh.
A solar panel's output is measured in Wp (Watt peak).

We use the term "watt peak" to describe how much electrical power a solar panel may generate depending on the strength of the solar radiation it receives. The angle of incidence between the sun's beams and the panel determines how strong the solar radiation will be. Consequently, it depends on:

- The season and time of day to establish the Sun's position: The power of irradiation increases with the thickness of the atmosphere.
- The solar panel's location, orientation, and tilt angle to calculate the angle of incidence between the sun's rays and its surface the more the solar rays arrive perpendicularly to the surface of the solar panel, the greater the transmitted power.

As such a photovoltaic installation, it can be referred to as having a "one-kilowatt peak" in the sense of "one-kilowatt maximum power". Like how peak power can be expressed outside of the SI as "P = 1 kWp" rather than "Peak = 1 kW" (DualSun, 2023).

5.4.3.2 Nominal power

When designing an installation, nominal power is crucial for properly sizing the cables and converters. The efficiency of the solar cell and, consequently, the nominal power per area (for example, kW/m2), are also significant if the available area is constrained. When comparing modules, the cost per unit of power (for instance, $/W) is appropriate.

The predicted yearly production (for example, kWh) per annual production assuming nominal power, that is, the capacity factor, is crucial for determining the location and physical orientation of a particular facility. For a specific plant, you can calculate the expected annual production price (for instance, $/kWh) (pdglx, 2021).

5.4.3.3 Open voltage

Open circuit voltage represents the full voltage of a voltage source. A voltage source's open circuit voltage is its full voltage value since it does not share any voltage with a load, therefore there are no voltage drops across a load as there would be where it was connected to one.

The open voltage for a solar panel is the highest voltage that a solar cell can create while there is no current flowing through it; in other words, it is the greatest voltage that a solar panel can produce without igniting any electrical fires or creating a power outage.

The ideal situation is between 30 and 58 volts. A panel with an open circuit voltage of under 30 volts is probably smaller and produces less electricity. A solar panel with an open circuit voltage of 31 V may outperform one with a voltage of 55 V, but it's crucial to note that the open circuit voltage does not determine which panel is better than another in terms of power production or longevity (Solar Edge Pros, 2022).

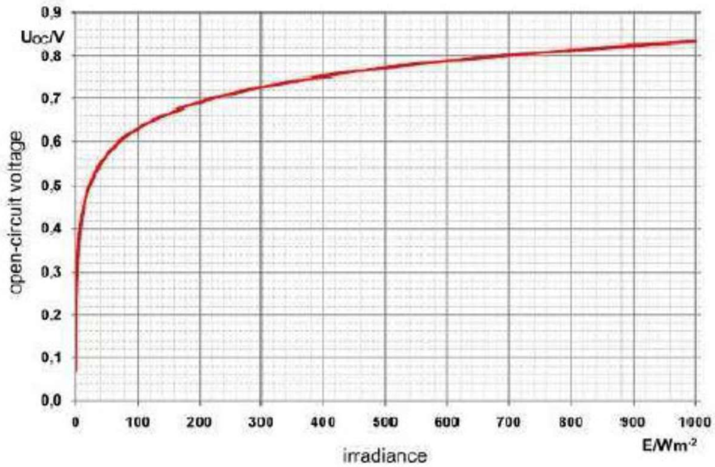


Figure 24: Open circuit voltage and irradiance graph

5.4.3.4 Open current

When the voltage across a solar cell is zero, or when the solar cell is shorted out, the current flowing through the solar cell is known as the short-circuit current. On Figure 25 below, the short-circuit current—often abbreviated as ISC.

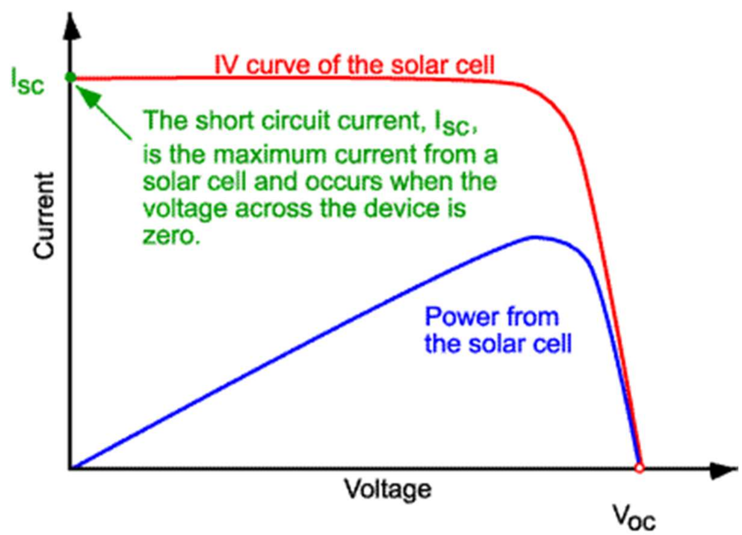


Figure 25: IV curve of a solar cell

Light-generated carriers are produced and gathered, which results in the short-circuit current. The short-circuit current and the current that produces light are equal for a perfect solar cell at most mild resistive loss mechanisms. Therefore, the largest current that can be drawn from a solar cell is the short-circuit current (*Short-Circuit Current | PVEducation*, n.d.).

Factors affecting Isc (De Rooij, n.d.):

- The power of the incident light source is described by the photons number. The Isc of a solar cell is directly proportional to the amount of light.
- The spectrum of the incident light.
- The solar cell's optical characteristics, including its ability to reflect light and absorb it.
- The likelihood of solar cell collection, which is mostly dependent on the base's minority carrier lifetime and surface passivation.

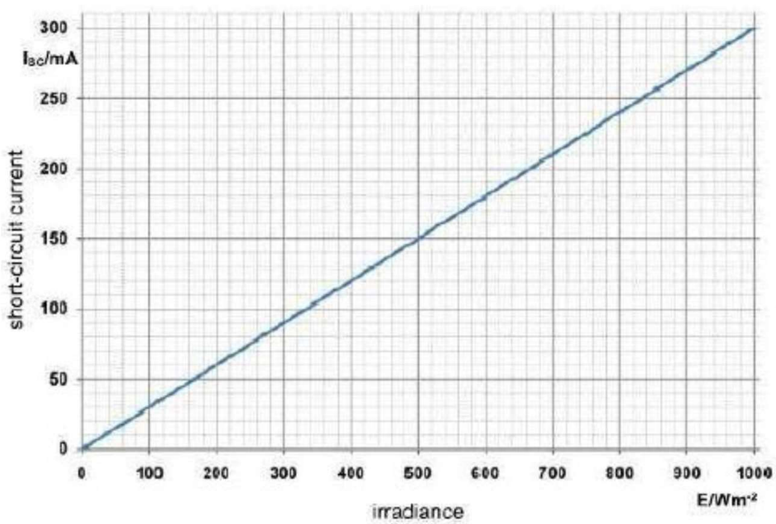


Figure 26: Irradiation, short circuit current

Figure 26 shows that the course of the short-circuit current is linear. Also, solar panels are short circuit proof. This means that they will not be destroyed by a short circuit. However, a short circuit against defective insulation, for example, can cause a large arc due to the high DC voltage (Verelst, 2021).

6 Inverter

One of the most important components of a solar power system is an inverter. It is a device that converts the direct current (DC) electricity produced by the solar panels into the alternating current (AC) electricity used by the households (*Solar Integration*, n.d.). The inverter consists of complex control electronics that convert electricity safely and quickly. However, inverters have other important functions that can reduce the total system performance.

6.1 Different inverter types

The first type is a string inverter, this inverter functions in an easy way. The string inverter as shown in Figure 27 converts the electricity produced by the solar panels into usable alternating current (AC) energy once it passes through the string. The solar panels' voltage and current are also controlled by the string inverter, resulting in stable and reliable energy production (Novergy, 2017). String inverters are more cost effective than central inverters. They are designed to be modular, so they can be easily scaled up or down as needed to accommodate changes in solar array size. In some cases, string inverters can achieve higher efficiencies because they can optimize the output of each string independently. The downside is that it is exposed to individual panel performance issues, and the failure of one panel can significantly impact the output of the entire string. They often lack the ability to monitor individual panels, making it difficult to detect problems at the panel level. And they have a limited input voltage range, which may not be suitable for some solar arrays.

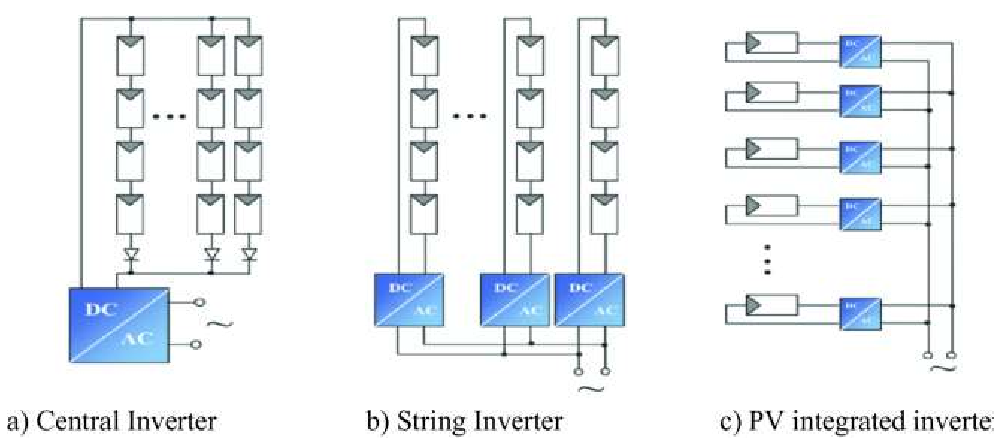


Figure 27: Different types of inverters

The second type is a central inverter, all strings of PV modules are connected to a central inverter as shown in Figure 27. Compared to the string inverter, this inverter does not have many additional advantages. However, the advantages of a central inverter are easy maintenance and very high efficiency. The disadvantage of connecting many modules in series is that if one or more modules in a string are shaded, the power generated by the entire chain is greatly reduced. It is also difficult to detect a fault in a string.

The last type is an integrated inverter, in this case, the direct current from each photovoltaic module is individually converted to alternating current by a integrated or mini inverter on the back of the module. Classic 230V wiring connects each module in parallel. Such inverters, usually square boxes with a side of 10 to 15 cm, are called module inverters and the modules "AC modules" or alternating current modules. The main advantages are lower installation costs and installation time by using standard AC wiring. In addition, since the modules are not connected in series, partial shading does not affect the overall performance (it only affects the individual module). As a result, the overall system efficiency is often better than previous systems. The downside is that the electronics are certainly sensitive to the high temperatures of the module, which also heats up the glued-on inverter. As a result, the lifetime of the module is reduced. In addition, the control of the grid coupling is more complicated for such a system (De Winne, 2012).

However, the inverter also has some additional tasks. For example, it will automatically start up when there is sufficient light and monitor the shutdown at night. It will also monitor the installation if the power level is higher than the rated power instead of shutting down. However, the inverter will also supply power to the control devices from the DC side. And it has many important safety features.

For summarization, the inverter closely monitors the various characteristics of the grid and shuts down as soon as irregular values occur that indicate the grid is failing. Therefore, it is important to research and maintain the inverters when they are installed.

6.2 Power optimizers

However, there is another technique for optimizing DC-DC systems. Since no inverters are used in the second case study, there is an opportunity to optimize the power output. This is made possible by something called a power optimizer. A power optimizer is a type of DC-DC converter designed to increase the amount of electricity that solar photovoltaic systems can produce. It does this by using Maximum Power Point Trackers (MPPT) to individually optimize the performance of each panel.

Compared to the microinverter, the power optimizer works on the same principle as the microinverter. Both systems attempt to isolate specific panels to improve system performance. A microinverter, which is installed on every panel, effectively combines a power optimizer with a smaller inverter in a single box. “Power optimizers are especially helpful when the performance of power-generating components in a distributed system can vary widely, for example, due to changes in equipment, shading from light or wind, mounting in different directions, or locations that are far apart.” (Prakhar et al., 2022; “Power Optimizer,” 2022) This could improve overall production during the rainy season. Since clouds in Zambia are frequent and variable during the rainy season.

6.2.1 MPP Tracking

Maximum Power Point Tracking, or MPPT, is a technique used by charge controllers to extract the most power possible from PV modules under certain conditions. Peak power voltage, also known as maximum power point, is the voltage at which a PV module can produce the most electricity. Solar irradiation, ambient temperature, and solar cell temperature all affect peak power.

The open-circuit voltage Voc and the short-circuit current Isc can both be determined from the I-V curve and the P-V curve for a PV module in Figure 28. The power delivered by the PV module is the result of voltage and current. At the two ends of the I-V curve, either the voltage or the current is zero, so the output power is also zero. At the knee of the I-V curve, where the product of voltage and current reaches its highest value, is the Maximum Power Point (MPP). The I-V characteristics of PV modules will change as the temperature and irradiation levels change. Consequently, the maximum power point will also change in real time. As a result, to get the most power out of the PV module, the MPP will always be the perfect power (Guo & Otieno, n.d.).

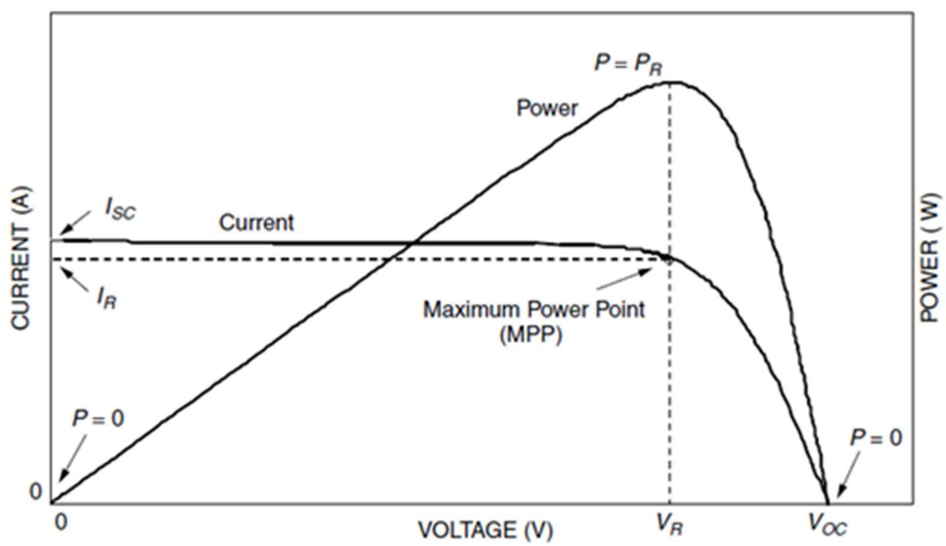


Figure 28: Graph MPP tracking

6.2.1.1 Batteries with MPPT usage

Batteries can be used by an off-grid PV system to power loads at night. Even if the MPP voltage of the PV panels is close to that of the fully charged battery pack, this is unlikely to be the case at sunrise when the battery is partially discharged. An MPPT can correct this mismatch if it starts charging at a voltage significantly lower than the MPP voltage of the PV panel. An MPPT can no longer run the panel at its MPP when the batteries are fully charged, and PV production is greater than local loads because there is no load to absorb the extra power. Once production matches demand, the MPPT must move the PV panel operating point away from the peak power point ("Maximum Power Point Tracking," 2023).

7 Battery

7.1 Battery energy storage system

An electrical storage resource capable of receiving electrical energy from an electrical resource and storing it for subsequent return of electrical energy to the grid is referred to as a battery energy storage system (BESS). Battery energy storage systems may include batteries, chargers, controllers, power conditioning systems and related accessories.

7.1.1 Why are battery energy storage system facilities important?

Serve as a driver for significant progress at both community and end-user levels, feeding into Global Green's renewable energy programs. Battery energy storage networks are certain to be the spark for long-term success in a new era of energy consumption, due to their ability to scale. As a result, demand for energy is growing as both connectivity and population increase. The environment has suffered greatly as a result, but switching to renewable energy sources can help solve supply and demand problems and reduce environmental damage. Considering solar energy installations as an example, the process is as follows (FSP global, 2022);

- Solar energy is produced through solar panels.
- They provide the necessary power to all the appliances that need it.
- The BESS batteries will be used to store any extra energy.
- The stored energy is used when solar energy is not available, such as at night.

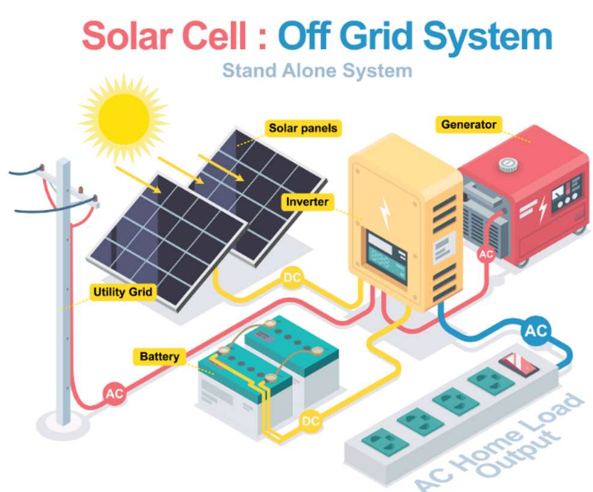


Figure 29: Figure standalone system

Battery Energy Storage System applications (FSP global, 2022):

- Peak shaving minimizes the risk of sudden energy usage increases.
- Disconnection from the grid in any circumstance that calls for it.
- Use load shifting to concentrate on stored energy consumption when the prices are greater. Ensure smooth transitions when renewable sources are/are not available.
- To save money and develop more environmentally friendly behaviors, embrace demand response initiatives.

7.2 Battery management system

A rechargeable battery (or collection of batteries), such as those used in electric vehicles, UPS systems and solar energy storage systems, is monitored and managed by a system called a Battery Management System (BMS).

The BMS is responsible for ensuring that the battery operates within safe parameters, prolonging its life and providing accurate information about the battery's state of charge, health, and current capacity. Its main functions can be simplified to ensure that the battery remains stable and safe. The current state of charge, overall health and remaining capacity of the battery are all details that the BMS can also communicate to a user or system. With this information, the system in which the battery is used can perform at its best.

7.2.1 How does BMS work?

A typical lithium-ion battery module is made up of packs of individual cells. This is because a single cell does not have the capacity to power the larger operations. Monitoring and maintaining these situations (where numerous modules are connected to form a battery) can be challenging as individual cells can charge differently. The BMS collects data from the batteries (in real time) and makes decisions based on this data. The parameters analyzed are as follows; voltage, temperature and current.

The BMS system will process these once they have been collected. The results of such processing are the data below:

- State of charge (SOC), a measurement of the battery's current state of charge while it is in use.
- State of health (SOH) is a measurement of the battery's state and capacity that determines how well it can keep a charge.
- Issues - keeping an eye out for any problems and fixing them.

The BMS then takes action to protect the battery based on the outputs, such as stopping charging when the SOC reaches capacity or shutting down the system when a cell reaches a certain temperature (Głogowski, 2022).

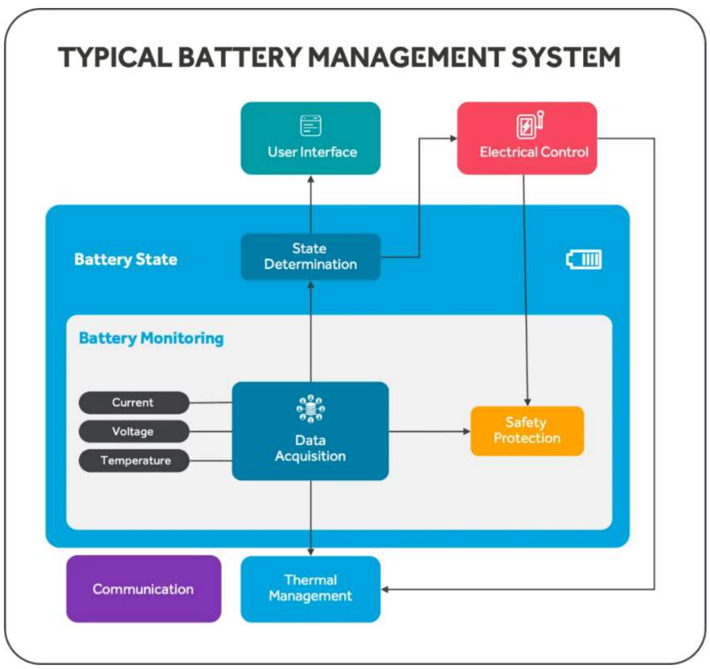


Figure 30: Picture typical BMS-system

In the absence of a BMS, the damage produce to the battery storage system are:

- Overcharging
- Exposure to too high or too low temperatures
- Over-discharge followed by recharging
- Short circuit

The consequences of this damage are a significant reduction in battery performance, a reduction in battery life, and the risk of fire.

7.3 Storing Solar Energy

Utilizing a storage system allows solar energy to be "shifted" from being used during the day to later in the evening or at night. This benefits grid management as well as the consumer directly. Less power is injected into the grid during periods of low usage thanks to the (partial) storage of solar energy. This minimizes the imbalance for which the grid operator must fix up. After all, at the highest solar position, most of the solar energy is produced around noon. However, household consumption is also at its lowest level.

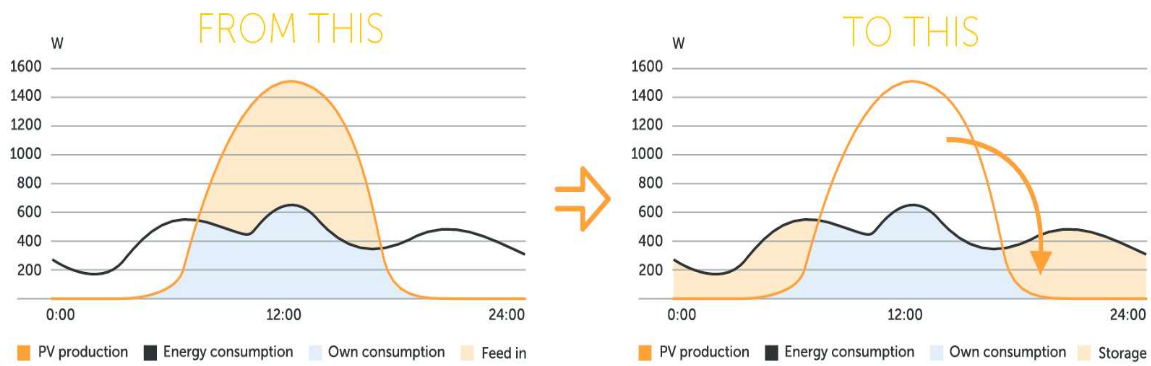


Figure 31: Solar storing yield

The effect of a battery system on household consumption is shown in Figure 31. The production of PV panels is shown in the image starting from the left. Production takes place between 6am and 6pm, while consumption without the battery system takes place during the same period.

When the battery system is added, this system improves, as can be seen on the right. In this graph we can see that the consumption has a distinct flow and is flatter, while the production is in the same interval. The electricity produced during the day can be used at the same time as in the early hours of the morning.

7.4 Conclusions

First, battery energy storage systems are essential for storing and delivering electrical energy from renewable sources to the grid. It can reduce environmental impact while helping to address supply and demand issues. It can be used for demand response programs, load balancing, peak shaving, and grid disconnection. Typically includes batteries, chargers, controllers, power conditioning systems and other ancillary equipment.

Second, a battery management system is responsible for ensuring that a battery or battery bank operates within safe limits, prolongs its life, and provides accurate information about the battery's state of charge, health, and current capacity. The BMS makes decisions based on data it continuously collects from the batteries. Without a BMS, the battery storage system can suffer damage that can reduce battery performance, shorten battery life, and increase the possibility of fire.

Overall, in some places where there is no access to electricity of any kind, an off-grid solar system may be the best source of power. When the sun is not shining, off-grid solar systems automatically generate electricity to charge battery banks during the day for use at night. A battery storage system is required for an off-grid solar system. In remote rural areas and applications where it is impractical or impossible to provide electricity for lighting, appliances, and other uses by paying the local electricity company to run power lines and cables directly to the home as part of a grid-connected PV system, off-grid PV systems are more practical to install.

Another important aspect about batteries for our cases in Zambia during the rainy season when the production of electricity is very low, during those months the hammer mill could be used few days per month, because the energy produced by the sun is not enough to start the hammer mill and that means loss of potential. But with these batteries, we can store this potential for couple days and then use the hammer mill to its full capacity for a few hours.

8 Maintenance of solar systems

8.1 Cleaning solar panels

Cleaning is the most common type of panel maintenance required. The panels can become covered with dirt, debris, and sand, especially after storms or extended dry periods. To ensure that solar panels receive the maximum amount of sunlight, they should be cleaned regularly to remove this material (Gerhardt, 2023).

An annual inspection to check the panels and make sure everything is working properly is a simple form of maintenance. Solar panels should be cleaned twice a year for the best performance. In an area where it rains a lot, the panels won't collect much dirt or debris, so cleaning may only be necessary once a year. However, in an area where it doesn't rain much, or where the solar panels tend to collect a lot of dirt or debris, more time should be allowed for cleaning. To avoid scratching the glass on the solar panel, never use an abrasive sponge or soap to clean it (Gobler, 2021).

Overall, solar panel maintenance is simple. Cleaning off any accumulated dust, debris, or sand will ensure that the panels function properly. It is also better to ensure that the panels have a strong warranty in case they break. The solar panels should continue to produce clean, sustainable energy at the highest possible efficiency for many years to come (Sendy, 2023).

8.2 Solar cable maintenance

Solar cables are the wires that connect solar panels to the inverter, battery, mini grid, and hammermill. They are exposed to harsh weather conditions such as heat, cold, rain, and UV rays, which can damage them over time. Damaged solar cables can reduce the efficiency, safety, and lifespan of your PV system, and can cause fire hazards, power outages, and costly repairs.

To maintain the solar cables and extend their life, the following are recommended:

- Clean the cables frequently. Over time, solar cables can collect dirt, dust, and other debris that can affect their conductivity and cause electrical problems.

Abrasive or harsh substances should be avoided as they can damage the connectors or insulation. Stepping on solar cables or dragging solar cables can cause physical damage that can reduce the overall system performance.

- Secure connections: Electrical resistance and heat buildup from loose connections can damage the cables and other PV system components. Check and tighten connections regularly using a torque wrench or screwdriver.
- Inspect cables for signs of damage, including frayed or exposed wires, cracks or breaks in the insulation, and loose or damaged connectors.
- Solar cables are exposed to UV light from the sun, which over time can degrade the insulation and cause it to become brittle. This can affect the functionality and safety of the cables. Use solar cables with UV-resistant insulation or cover the cables with a UV-resistant conduit or cover.
- Secure the PV cables and prevent them from sagging or dangling by using cable ties or other support systems such as cable trays, clips, or hooks.

9 Data logger

A data logger is a tool that records and stores data over a period. In the case of solar systems, a data logger is used to track and record the operation and performance of the solar system. It collects information on variables such as temperature, humidity, sunshine intensity, solar radiation, and the amount of energy produced by the solar panels. This data can then be used to optimize the performance and efficiency of the system.

Essentially, a data logger is connected to various components of the solar system, such as solar panels, inverters, meters, etc., and collects data periodically. This data is then sent to a central database, server, or can be stored locally for analysis. The information is provided to the site owner to monitor, optimize, and improve the performance of the solar panels. The data logger provides insightful data on the operation of the solar system.

Advantages of using data loggers (OMEGA Engineering inc., n.d.):

- Data logging can be done manually with continuous human observation, but this method takes time and is prone to human error. You can save time and money by using a data logger to take measurements accurately and automatically at set intervals without the need for human intervention.
- It only takes a few clicks to transfer data from a data logger to your PC. Data from wireless and LAN loggers is sent instantly to your PC for viewing.
- Overlays that allow you to view data from more than one logging run simultaneously. Data is initially displayed as a graph but can alternatively be viewed in tables of readings. Data can be easily exported to external tools for further investigation.
- A data logger is typically used in a solar PV data acquisition system (DAS) to concentrate and collect all the data from the field devices and then log this data in a format that can be analyzed.

II Analyze and modeling

All modelling, i.e. the electricity production from the photovoltaic panels and the response of the battery/PV system to the demands of the grid, was carried out using SAM software. SAM (System Advisor Model) is an energy modelling and simulation software package developed by the National Renewable Energy Laboratory (NREL) in the USA. It allows users to model and analyze energy systems of all sizes, including photovoltaic, wind, solar thermal and energy storage systems.

In the two case studies studied, the lack of a data logger is a drawback, as information on electricity production and consumption is missing. However, the SAM software allows access to the National Solar Radiation Database with a fine spatial resolution (30 min).

In each case, the modelling was performed using a set of satellite-derived solar radiation measurements (global horizontal, direct normal and diffuse horizontal irradiance) and meteorological data available at the sites (Kitwe and Kampekete respectively) with a temporal resolution of 30 min for the years 2017, 2018 & 2019. The datasets used are from the METEOSAT IODC satellite, using the Physical Solar Model (PSM) V3, with a spatial resolution of 4 km. The unavailability of Typical Meteorological Year (TMY) data, which best represents the median weather conditions over a period of several years, limits the generality of information that can be derived from the models. In our case, the output of the modelled PVs is generated by the Perez sky diffuse model, which is the most widely used and best suited to the available dataset. Each sky diffuse model has its own set of approximations and errors (Muneer, 1990).

For the most part, the simulation results have been post-processed by an in-house Python program to take full advantage of the results. It is important to note that the interpolations and other functions used by Python are sources of inaccuracy. Assuming the program works as intended, an error of 0.001 KWh can be estimated.

10 CASE 1: Copperbelt University

The first is a study for CBU (Copperbelt University). In this case there are 50 solar panels. There is no battery installed and the electricity generated is only used for the hammer mill. However, there are no changes between seasons. In this case we don't have any information about an installed inverter, bypass diodes or possible optimizers. So, we assume, as in the previous case, a basic system without MPPT tracking or any additional features that might improve the overall system performance. The system specifications are given in 10.1 System specifications CASE1.

The whole system is in Kitwe, Zambia as shown in Figure 32. The coordinates are 12°46'59.3"S 28°15'55.2"E. In the small blue house is the hammermill installation located.

Figure 32: Google maps geographical photo CBU case study

10.1 System specifications CASE1

10.1.1 Solar PV

Shandong Dejian 255Wp-60P[3]	
Cell Type	Polycrystalline
Cell Size	/
Panel Dimension (H/W/D)	1634x982x40 mm
Maximum System Voltage	1000 V
Inclination	15 °
Temperature	/
Maximum Power (Pmax)	255 Wp
Voltage at Maximum Power (Vmpp)	30 V
Current at Maximum Power (Impp)	8,33 A
Open Circuit Voltage (Voc)	36 V
Short Circuit Current (Isc)	9,25 A
Panel Efficiency	/
Power Tolerance (Positive)	+3%
Operating Temperature Range	/
Temperature Coefficient of Pmax	/
Temperature Coefficient of Voc	/
Temperature Coefficient of Isc	/

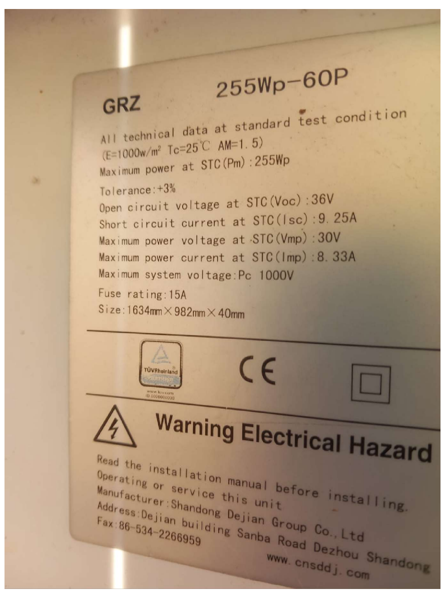


Figure 33: Picture provided by Mr. Fumpa

[3] Data retrieved from WhatsApp as shown on **Error! Reference source not found.** provided by Mr. Fumpa

10.1.2 Hammermill

Solar Powered Milling Machine DJ-TMF[4]	
Model NO.	DJ-TMF
Voltage	48V DC
Power rating	6,9 kW
Press Materials	Corn
Trademark	Dejian
Efficiency	/
Length of cycle	4-8 min[5]

Figure 34: Image from the manufacturer's website and Abel Fumpa

[4] Shandong Dejian Group Co., Ltd. (n.d.). Solar Powered Milling Machine. Made-in-China.Com. Retrieved May 9, 2023, from https://shandongdejian.en.made-in-china.com/product/vXsJIBhrCuUz/China-Solar-Powered-Milling-Machine.html

[5] This value is dependent on the amount of maze input.

10.2 System configuration

Compared to the other case, this system is completely different. There are no households connected to the system. All the energy from the 50 solar panels is used to power the hammer mill. Thus, the total production of the system is 12,750 kWp during all year long.

However, the entire system operates on DC and does not use AC. The DC from the solar panels is connected to a central control system:
"The Central Control System (CCS) is also an energy management system. It can control and regulate the voltage. The power from solar panels will be divided into two directions, one is DC48V to drive the motor directly, the order is to charge the super capacity when the sunlight is good. The supercapacitor will discharge quickly to stabilize the DC motors when the sunlight is weak. The supercapacitor also ensures the large starting current of the motor by discharging quickly. The CCS system is also equipped with monitoring function, which can provide the operating data all the time to ensure the safety of the whole system". (Shandong Dejian Group Co., Ltd., n.d.)

In all our calculations and analyses, we neglect this supercapacitor because its contribution to the overall system performance is very small.

The production schedule is from 10:00AM to 4:00PM, this is the same throughout the whole year. However, there is a big difference between the average production, during the dry season there is an average production of 800 kg maze meal per day. While during the rainy season there is an average production of 120 kg maze meal per day. This is also because during the rainy season there is much more cloud cover and alternating irradiation from the sun, just as in the other case study.

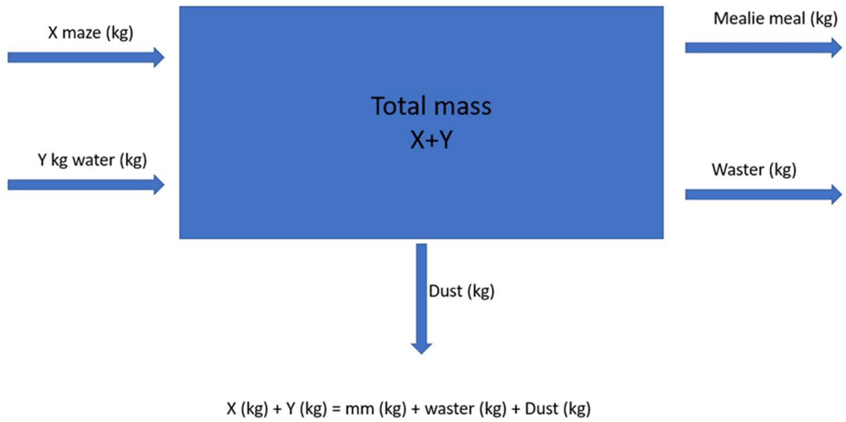


Figure 35: Total mass introduced in the Hammer mill

The hammer mill's efficiency is not 100 %. That implies that not all the products we introduce will be received in the same quantity. There are gaps in the system that reduce total efficiency by 10% and prevent it from being entirely sealed. The ingredients we use in the hammermill are maize and water, and the result is a mealie meal, but we also generate a substantial amount of non-consumable waste.

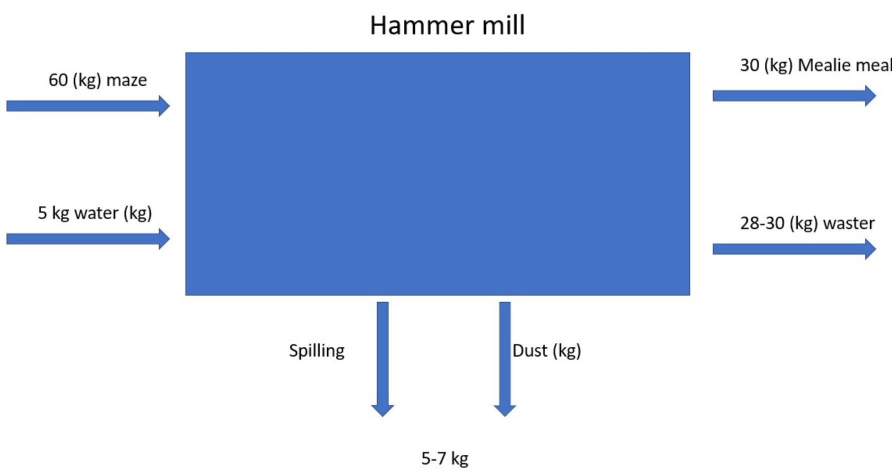


Figure 36:Example of mass introduced in the Hammer mill

Figure 36 provides a better example of how the hammer mill production process operates. 30 kg of mealie meal is produced from 60 kg of maze as input. It's simple to view why this process only operates at 50% efficiency.

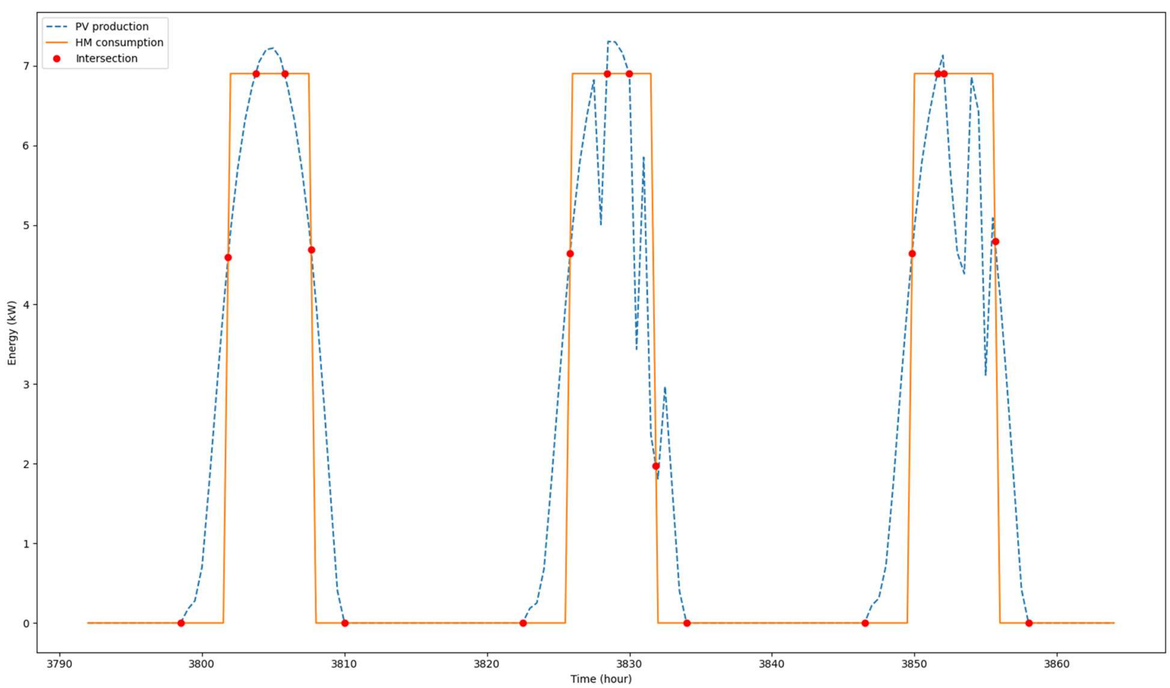
10.3 Analyzes

All the modelling, i.e. the production of electricity by the photovoltaic panels and the response of the battery/PV system to the demands of the grid, was carried out using SAM software. SAM (System Advisor Model) is an energy modelling and simulation software developed by the NREL (National Renewable Energy Laboratory) in the United States. It allows users to model and analyze energy systems of all sizes, including photovoltaic, wind, solar thermal and energy storage systems.
In the two case studies studied, the lack of a data logger is a disadvantage, as information on electricity production and consumption is missing. However, the SAM software allows access to the National Solar Radiation Database with a fine spatial resolution (30 min).

In each case, the modelling was carried out using a set of solar radiation measurements derived from satellites (global horizontal, direct normal and diffuse horizontal irradiance) and meteorological data available at the sites (Kitwe and Kampekete respectively) with a 30 min temporal resolution for the years 2017, 2018 & 2019. The datasets used are from the METEOSAT IODC satellite, using the Physical Solar Model (PSM) V3, with a spatial resolution of 4 km. The unavailability of Typical Meteorological Year (TMY) data, which best represents the average meteorological conditions over a period of several years, limits the generality of the information that can be derived during modelling. The production of the PVs to be modelled is generated in our case by the sky diffuse model of Perez, which is the most widely used and most appropriate for the available data set. Each diffuse sky model has its share of approximations and errors (see (Muneer, 1990)).

In most cases, the simulation results have been post-processed using a home-made python program to exploit the full depth of the results. It is important to note that the interpolations and other functions used by Python are sources of inaccuracy. Assuming the program works as designed, an error of 0.001 KWh can be estimated. All things being equal, many system-specific factors, such as solar panel soiling, are not considered in our model. The models used, although archaic, should give a good idea of the behavior of the systems. However, to give our results more weight, we would have liked to confirm our models by collecting information directly on site to confirm or invalidate our model. Unfortunately, this was not possible.

The aim of this study is to analyze and evaluate the effectiveness of the current system configuration. The study is divided into three parts corresponding to three different points of view. Firstly, the operation of the system from an energy point of view, secondly from a user point of view and finally from a system point of view. As far as the system is concerned, it should be noted that the hammer mill operates at 7kW in all or nothing mode (below the orange line it stops, if the blue line reaches the top of the orange line, the hammermill works). In fact, the consumption profile is as shown in Graph 1 below. The analysis takes a fixed consumption time range of 6 hours, as explained earlier.



Graph 1: Consumption profile

The study of energy production and consumption will lead us to examine three specific areas. To help the reader understand what these areas correspond to, a diagram is provided in Figure 37 below.

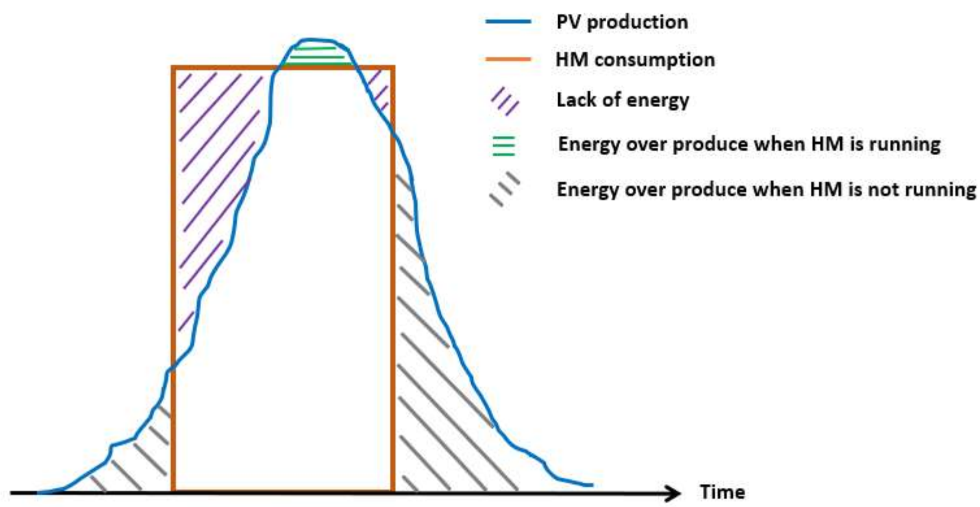


Figure 37: Hammermill working area

10.3.1 Study of the system from an energy point of view

First, the amount of energy not used by the system is examined. The simulations conducted for the years 2017, 2018 and 2019 give the results shown in Figure 38.

DELTA CONSUMPTION PRODUCTION 2017 (kWh) :	14083	14.70%	PRODUCTION 2017 (kWh) :	16511	CONSUMPTION 2017:	2428
DELTA CONSUMPTION PRODUCTION 2018 (kWh) :	14184	13.41%	PRODUCTION 2018 (kWh) :	16380	CONSUMPTION 2018:	2196
DELTA CONSUMPTION PRODUCTION 2019 (kWh) :	14000	16.45%	PRODUCTION 2019 (kWh) :	16755	CONSUMPTION 2019:	2756
DELTA CONSUMPTION PRODUCTION AVG (kWh) :	14089	14.86%	PRODUCTION AVG (kWh) :	16549	CONSUMPTION AVG:	2460

Figure 38: Calculated consumption and production profile

First, we can see in Figure 38 that the total energy production for one year is 16,549 kWh on average. This production is stable over the three years studied (+- 206 kWh), which corresponds to a relative variation of 1.2% if the average production over one year is taken as a reference. Of this energy produced, an average of 2,460 kWh is consumed by the hammer mill, leaving an average of 14,089 kWh unused over the three years, i.e., 85.14% of the total energy produced by the system over one year.
A significant amount of energy is therefore wasted. To give an idea of what this represents, the average annual electricity consumption of a French household is

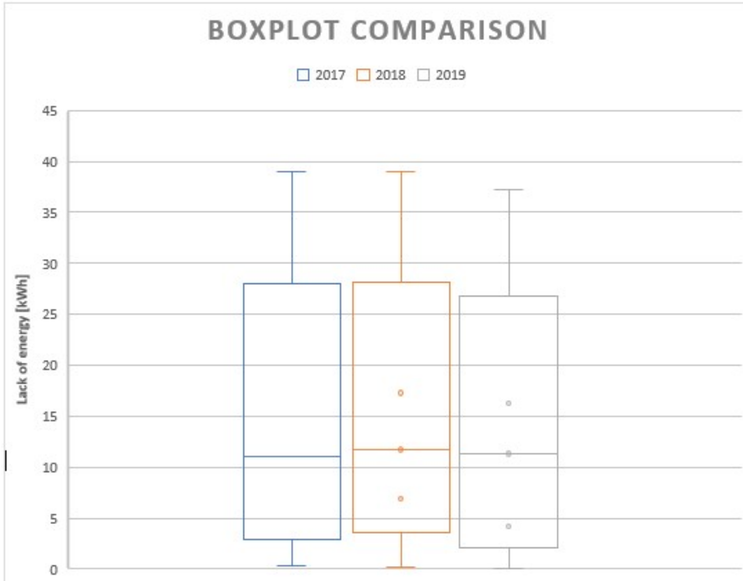
around 4,500 kWh, which means that 14,000 kWh represents more than three years of electricity consumption for an average household in France.

Another important aspect is the distribution of electricity production during the operating hours of the hammer mill. In fact, it is necessary to know whether this amount of energy is since the system as a whole is undersized (most of the energy produced is wasted when the hammer mill is not running) or oversized (most of the energy produced is wasted when the hammer mill is running).

Year	Energy over produce (kWh) (not in work hour)	Energy over produce(kWh) (HM lack power)	Energy over produce(kWh) (HM is running)
2017	5392.27	8509.46	181.63
2018	5396.29	8501.24	248.04
2019	5195.07	8539.49	265.12
Average	5327.87	8516.73	231.60

Figure 39: Energy overproduction

From Figure 39 the amount of energy overproduced when the hammer mill is in operation is small (a factor of 20) compared to the energy not used when the hammer mill is in operation or when it is not within the operating time window. In these last two cases, the overproduced energy is of the same order of magnitude. Overall, we can hypothesize that the system appears to be undersized from this point of view. To support or refute this hypothesis, it is possible to examine the distribution of the missing energy required to operate the hammer mill. To do this, a graph was created comparing three box plots for each year. The box plots show the quartiles and extremes of each data set, allowing quick comparison of trends and dispersion.



Graph 2: Boxplot comparison

According to Graph 2, which compares several box plots, the box plots have globally the same "spread" and similar medians (less than 1 kWh difference), indicating a similar dispersion of the missing energy over the three years. The extreme values are also similar (less than 3 kWh difference). Thus, the annual climatic variability does not seem (according to this data set) to have a major influence on the missing energy for the operation of the hammer mill. This observation is favorable for the study of the system, especially for the generalized one.

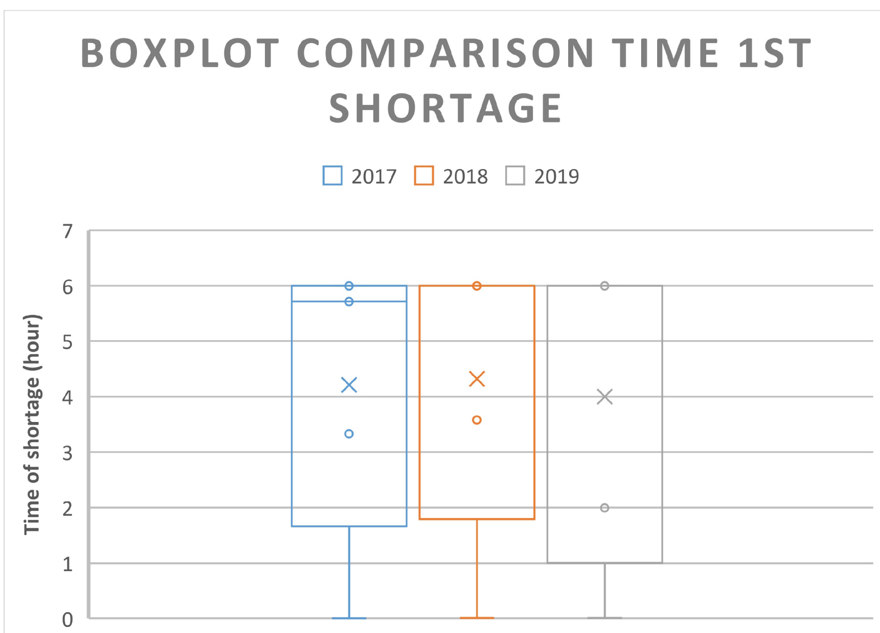
In addition to this aspect, Graph 2 also shows that in 50% of the cases encountered, the missing energy to operate the hammer mill is greater than approximately 11.5 kWh. This confirms the previous hypothesis that the current system is undersized. According to these analyses, the current photovoltaic system does not meet the energy needs of the hammer mill efficiently and optimally. Only a small proportion of the energy produced by the system is used, resulting in a significant waste of energy.

The amount of excess energy produced when the hammer mill is operating is significantly less than the amount produced outside of operating hours or when the hammer mill should be operating but is not due to lack of energy. In addition, the distribution of the amount of energy missing to operate the hammer mill shows a strong similarity over the three years studied, indicating a tendency for the problem to repeat itself.

In conclusion, the analysis of the graphs clearly shows that significant improvements are needed to optimize the performance of the photovoltaic system to power the hammer mill efficiently and sustainably. It is essential that measures are taken to reduce energy wastage, maximize the use of the energy produced and ensure a stable energy supply for the hammer mill.

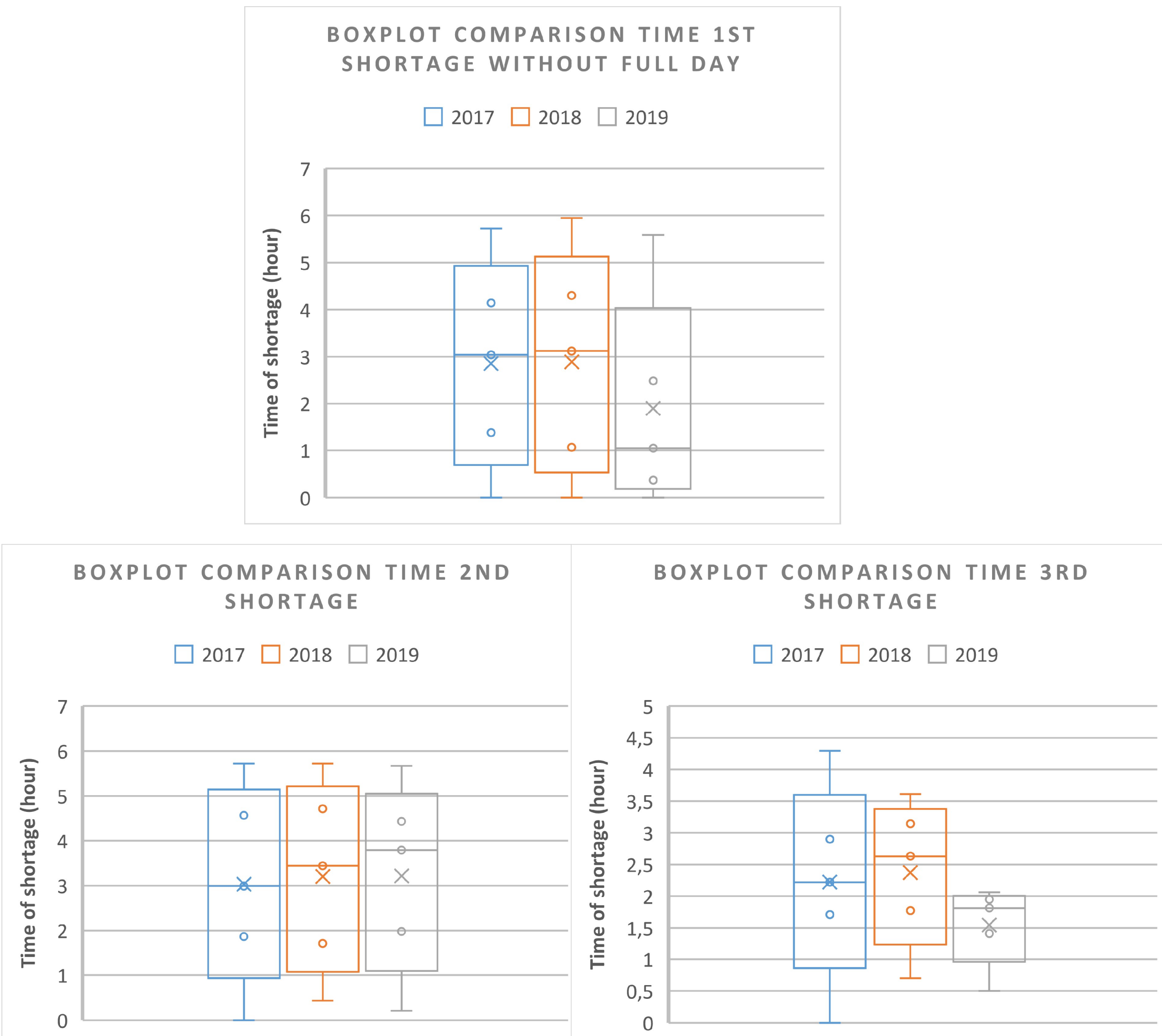
10.3.2 Study of the system from the user's point of view

As already mentioned, the first vocation of the system is to operate the hammer mill when the local population needs it to produce flour. Therefore, the concepts of availability and the number and duration of breakdowns are important. To illustrate this, Graph 3 below compares how the number of breakdowns is distributed over the three years.



Graph 3: Boxplot comparison 1st shortage

The median is confused with the third quartile, which in turn is confused with the maximum value (which corresponds to 10 H, working hours of the hammer mill) for the three years. This observation underlines the fact that more than half of the first cuts correspond to days when the hammer mill is not sufficiently supplied to operate. These box plots also highlight the fact that the duration of the first cut is between 0 and 6 hours. We can see that 75% of the first cuts are longer than 2.2 hours. It was decided to plot the box plots for the first cut without considering the days when the hammer mill simply could not operate. In this way we remove the "parasitic" values that have shifted the corresponding values of our medians and quartiles. It is now possible to see in the graph below, that the median time for the first cut was 3 hours for 2017 and 2018.



Graph 4: Boxplot comparison of different shortages

Regarding the second denominations in the left graph the median for the 3 years is above the 3 h. In the right graph, we observe that the median is located around 2 hours.

We also observe that the outage times of the third denomination are more dispersed in 2017 than in 2018 and then in 2019. The duration of outages can therefore vary from one year to another. This variation can also be explained by the absence of devices (by-pass diode type, DC optimizer) to compensate for any variation in the environment of the solar panels (shading).

It is also interesting to study the number of blackouts that the system must cope with each year.

Year\N° shortage	1	2	3	4
2017	365	41	10	1
2018	365	49	6	0
2019	365	68	4	0
Average	365	52	6	0

Figure 40: Table of blackouts

On average, 14% of the days of the year have two breakdowns, but there is at least one breakdown per day (the hammer stops and cannot work on that day). Overall, we can conclude from this analysis that although the number of breakdowns is not very high, with a minimum of 1 per day and a maximum of 4 (Figure 40: Table of blackouts), their duration is significant, as shown by the positioning of the medians. In fact, we can say that half of the interruptions last more than 2 hours. Therefore, depending on the year and the use of the hammer, the user can have a significant negative impact by being exposed to cuts that last more than a third of the time in half of the cases.

	January	February	March	April	May	June	July	August	Septembe	October	Novembe	December
1	0	0	0	88.38	75.54	68.46	269.52	114.3	0	55.98	0	0
2	0	0	24.6	142.8	217.02	0	153.24	39.6	241.86	0	0	0
3	0	0	102.48	96.66	188.88	0	0	0	175.8	0	0	0
4	0	0	40.26	0	170.88	0	50.7	0	162.18	0	0	0
5	0	0	49.14	183.54	132.18	240.36	107.4	0	50.7	0	0	0
6	0	0	0	201.96	136.02	259.32	170.4	0	0	0	0	37.38
7	0	0	0	120.96	165.66	30.96	214.38	240.3	64.98	0	0	74.82
8	0	0	0	278.22	195.42	0	186.3	151.32	138.48	0	0	55.14
9	0	0	79.38	175.14	202.62	235.68	181.26	239.46	0	0	0	0
10	0	0	0	196.44	145.86	212.28	144.72	46.92	0	0	0	0
11	0	0	47.22	99.72	80.76	66.24	0	175.92	0	0	0	0
12	0	0	0	106.2	0	197.76	271.02	153.72	102.36	0	73.08	0
13	0	12.24	0	83.88	0	78.84	58.5	190.32	134.88	0	0	0
14	0	0	120.18	34.26	51.12	0	92.88	0	54.36	165.84	135.84	0
15	35.64	0	0	0	93.66	0	66.72	186.48	0	0	0	0
16	0	0	0	110.94	86.7	76.5	0	0	0	0	0	0
17	0	0	7.26	0	90.84	252.54	285.48	0	0	0	0	6.96
18	0	0	196.26	0	0	169.08	268.98	0	0	0	0	0
19	0	0	149.46	0	142.44	145.2	59.4	160.32	62.88	0	175.08	30
20	0	0	0	0	228.96	256.14	0	275.76	61.74	0	48.78	0
21	0	0	52.38	0	113.34	183.72	165.12	277.74	91.62	0	0	0
22	0	164.64	81.42	26.76	111.78	50.22	0	0	0	79.98	0	0
23	0	0	0	108.66	119.34	0	0	0	0	0	5.82	0
24	0	0	0	0	120.3	162.9	0	0	100.38	0	74.1	0
25	0	0	0	0	80.34	132.24	65.52	0	0	0	0	0
26	0	0	23.58	0	0	279	0	173.34	0	0	0	0
27	0	0	0	0	0	179.58	285	121.8	0	0	0	0
28	0	0	0	0	0	163.86	318.96	279.72	35.28	0	0	0
29	0		231.78	199.92	267.12	172.92	276.12	146.58	138.66	0	0	0
30	0		42.78	111.24	0	194.82	232.86	0	70.8	0	0	0
31	0		0		55.14		248.94	0		51.3		0

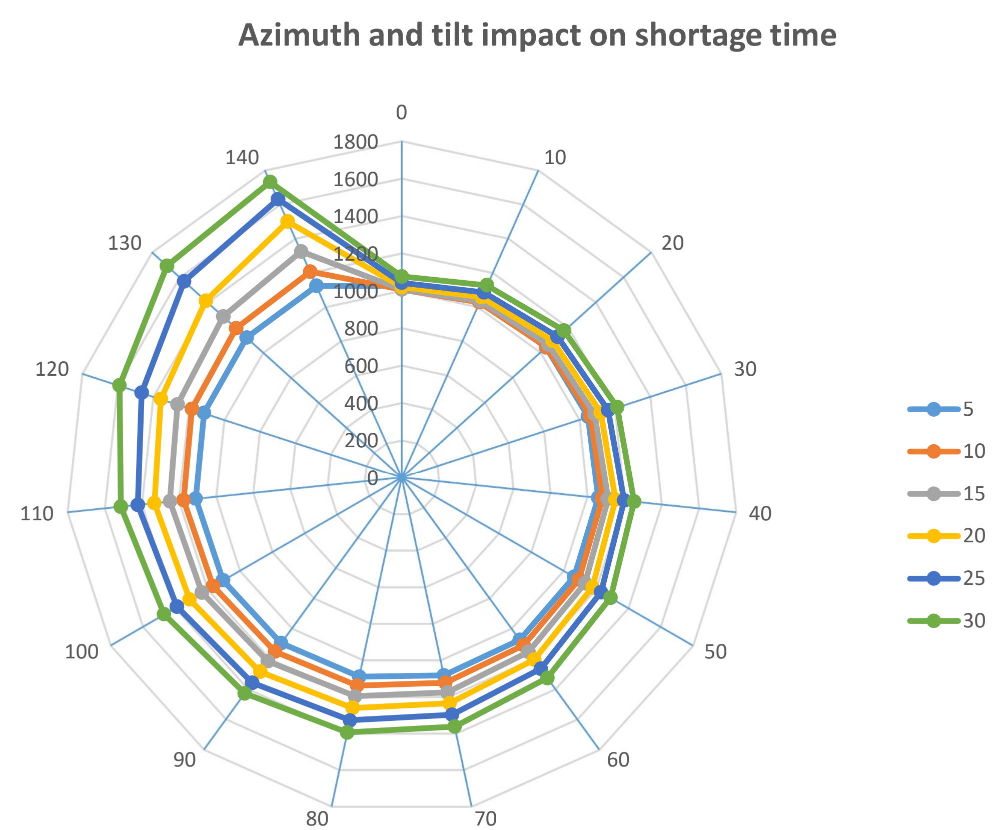
Figure 41: Maximum amount of minutes the hammermill can operate

If we look at Figure 41, for example, the year 2017, we see that the availability of the hammer mill is heterogeneous. Especially during the rainy season, the number of days the hammer mill can work is very limited. For the month of January, the hammer mill was only able to work for 35.64 minutes and only on one day, which makes its use almost impossible in practice.

Another point of view can be taken from the system itself. First, it should be emphasized that the data we have is partial. However, our exchanges with our Zambian partners seem to confirm the absence of MPP tracking and DC optimizer in the system. However, the latter can play an important role, as explained in the relevant sections above.

However, it is difficult to assess the benefit that these can bring to our system, particularly as it can be strongly influenced by specific local conditions, such as the shading caused by a tree close to the solar panels. However, even if it is difficult to estimate a percentage, we can admit that a gain of between 0 and 25% would be possible. (By combining MPPT and DC optimizer). It may be worthwhile to carry out further studies and experiments to find out what is the case. The absence of bypass diode type devices can also be very detrimental to the system. As the system studied for this case study does not have any of these "optimization" elements, its effectiveness is reduced.

The configuration of the system (inclination and azimuth) must also be evaluated if you want to get the most out of the system. In fact, in our case, the optimal configuration is not necessarily the one that produces the most electricity per year. It corresponds to the one that is most likely to reduce the power outage time. Graph 5 shows the average annual shortage time in hours (for the year 2017) as a function of the azimuth (0 to 140°) and the tilt of the solar panels (5 to 30°).



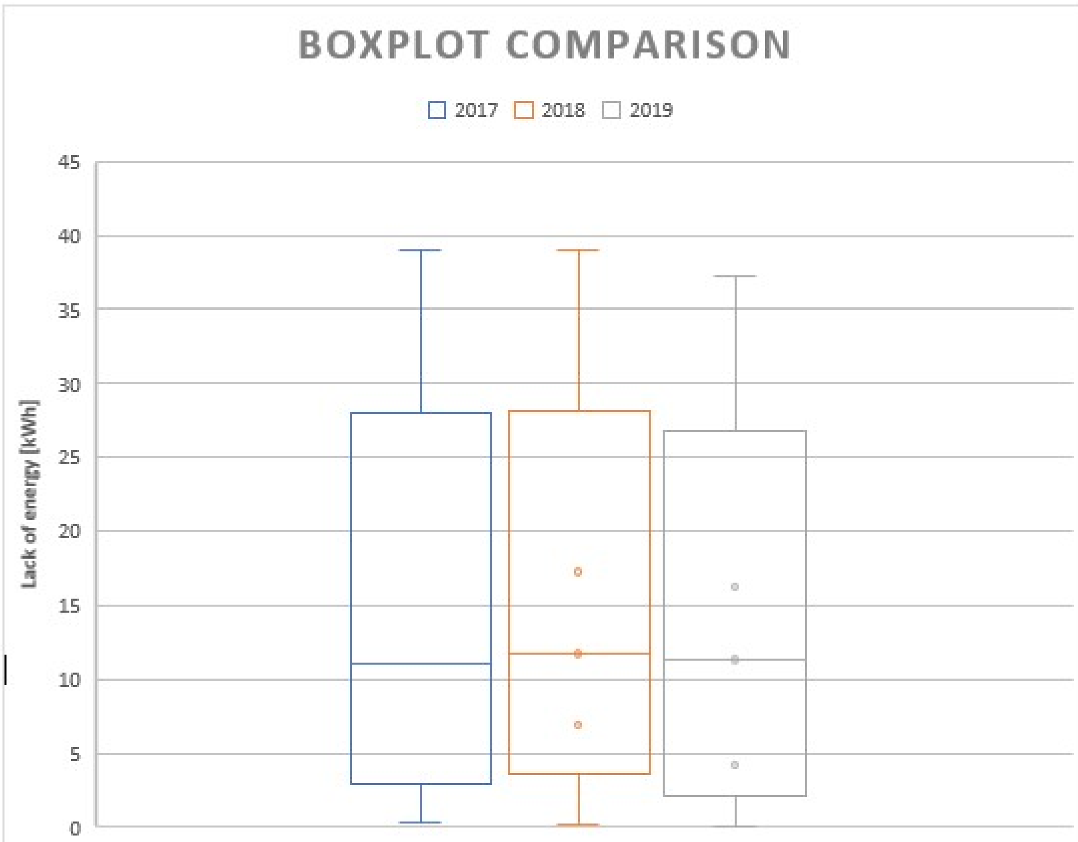
Graph 5: System Performance Related to Positioning

In Graph 5, an increase in both tilt and azimuth independently result in an increase in downtime. After comparing the possible configurations, the current configuration of the system (Azimuth = 0°) and Inclination 15° is the optimal configuration, which allows to reduce the downtime as much as possible.

In conclusion, these results highlight the need to take measures to improve the energy efficiency and energy management of the system. This could include the use of more efficient technologies, the installation of an energy storage system.

10.4 Improvements

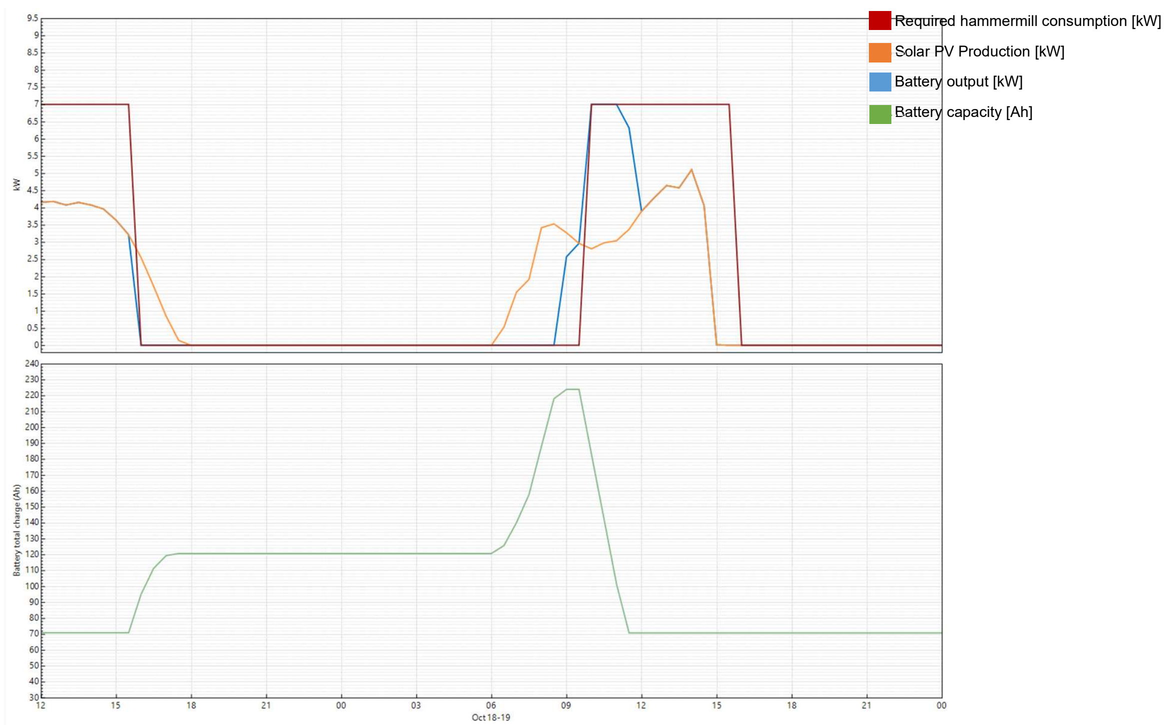
After a complete analysis of the current system, the next step was to determine what improvements could be made to the efficiency of the system. As shown earlier, there is a huge shortage during the rainy season. A battery system could solve this problem. To get an idea of how big the impact could be, it is necessary to create a model that compares the current system with the current system with a battery.



Graph 6: Boxplot comparison yearly lack of energy

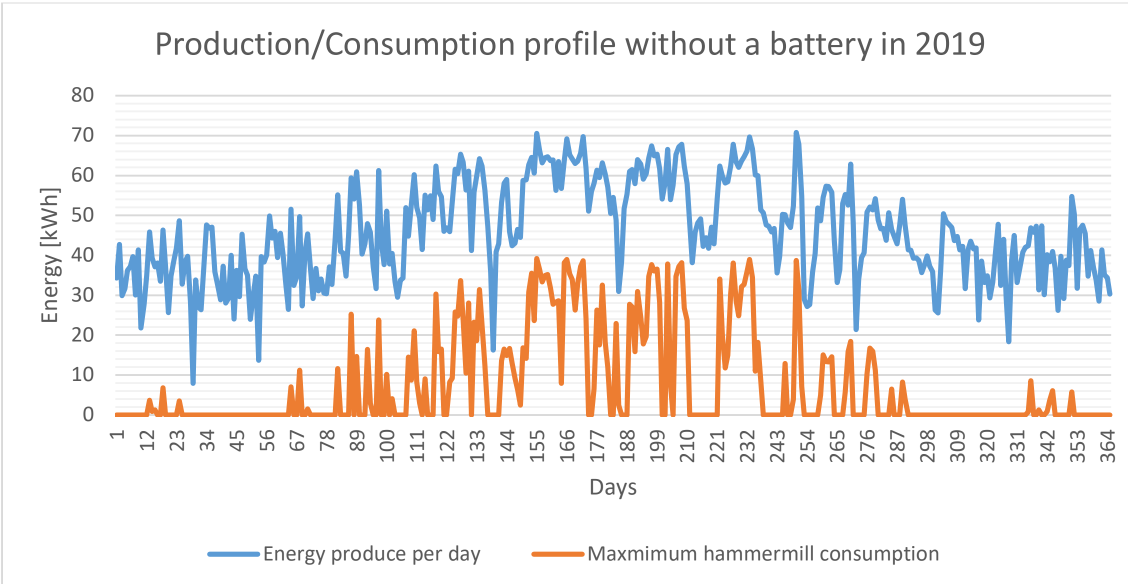
As shown in Graph 6, the boxplot clearly shows the lack of energy. The median of the boxplot can be used to determine the capacity of the battery. As a result, the average median is approximately 12 kWh. Therefore, the model uses a battery with a capacity of 12 kWh or 250 Ah. The minimum state of discharge is 30%, which is the optimal percentage of discharge for the longest battery life. If the minimum state of discharge were to be lower, there would be some malfunctions in the battery.

Given the complexity of battery charging behavior, our analysis uses a simple way to predict charging behavior. This means that the battery will be fully discharged (till the 30%) when it has the potential to produce with the solar panels a total output of 7 kW. As shown in Graph 7, the blue line is the added power to the system. This means that without a battery the hammermill couldn't work that day. Now the battery will load up to 225 Ah before 8AM and discharge from 8AM to give the additional power to achieve the 7kW.

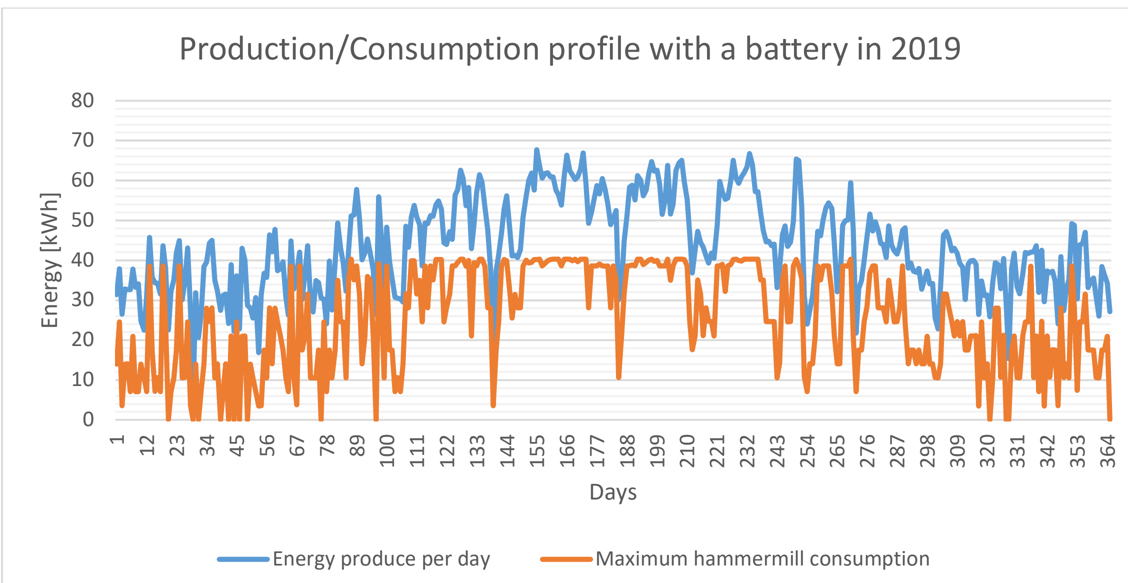


Graph 7: Influence from a battery on the system

It's important to realize that this is a very simple way to predict the charging behavior on a fixed hammermill consumption. If there is more data on the consumption side, or if there is a consumption schedule, this could optimize the prediction of charging behavior. As a result, better predictions could optimize the consumption and production profile to get the best system performance.



Graph 8: Production/Consumption profile without a battery in 2019



Graph 9: Production/Consumption profile with a battery in 2019

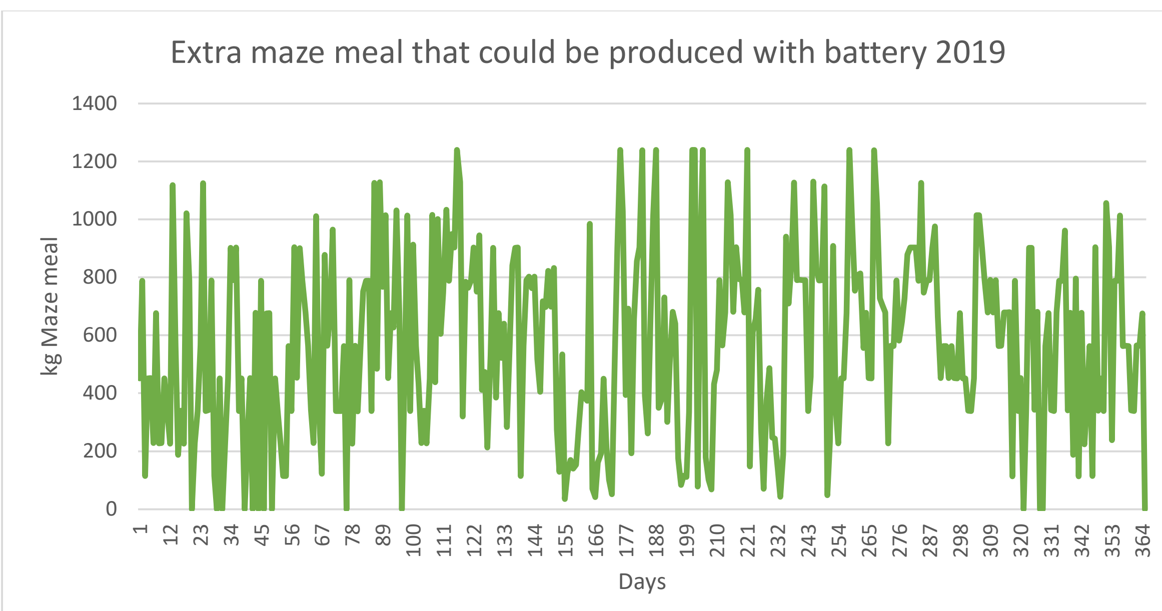
Graph 8 shows the production and consumption profile without the battery. This is just a simple graph, where the gap between the two lines represents the lost power. While Graph 9 shows a much better result, the maximum production of the hammermill increases significantly. So, at first glance, there is clearly room for improvement. There are extra production opportunities with the battery, especially during the rainy season.

Hammermill working minutes with battery 2019

	January	February	March	April	May	June	July	August	September	October	November	December
1	120,24	60,78	210,54	120,42	210,6	336,66	240,72	181,02	121,92	150,24	270,72	210,3
2	210,36	120,24	180,78	180,24	240,72	338,52	330,48	300,9	301,2	210,6	240,66	330,06
3	30,66	240,3	150,3	307,98	270,36	345	300,66	270,72	330,42	243,06	210,96	91,02
4	120,24	210,72	91,08	300,18	330,36	344,94	90,72	181,38	210,6	315,66	180,96	180,54
5	120,48	240,78	60,72	180,48	330,36	345,24	180,24	240,96	210,72	330,36	211,08	60,6
6	60,72	90,24	330,18	0,18	338,34	330,36	270,78	211,74	330,48	330,3	180,96	212,22
7	180,24	120,3	90,3	336	345,18	336,6	330,54	210,96	345	240,66	210,9	30,36
8	60,54	0,54	32,58	270,3	345,12	342,24	330,6	180,84	330,12	240,6	150,12	180,6
9	60,66	60,54	330,24	90,24	330,12	345	333,24	330,6	303,66	240,72	150,48	91,38
10	120,18	120,66	150,42	330,36	342,66	345,18	330,3	331,02	92,58	210,36	180,96	150,72
11	90,18	0,6	181,26	150,24	180,36	345,12	345,18	334,62	60,42	300,3	180,96	150,24
12	60,3	180,72	270,42	150,36	337,8	345,18	345,12	275,82	120,3	255	181,08	30,48
13	330,12	0,18	90,42	60,6	330,24	330,36	333,6	330,36	120,36	210,66	30,36	241,02
14	150,72	210,36	90,3	90,54	345,18	345,3	338,58	333,66	180,24	210,72	210,36	90,66
15	60,9	0,54	90,36	60,48	345,12	345,06	343,56	344,94	330,6	240,54	90,3	120,36
16	90,54	180,18	150,18	120,18	330,12	345,24	345,18	345,18	301,08	330,6	120,48	90,24
17	60,18	180,42	0	270,84	240,54	341,4	340,02	342,96	330,36	210,54	0,66	330,36
18	330,24	0,36	210,66	240,42	240,72	345,12	342,54	340,8	330,3	120,48	90,42	240,96
19	210,6	120,18	60,3	341,88	30,48	339,36	330,3	345,18	330,42	150,18	240,3	63,6
20	1,32	90,42	150,3	341,88	150,54	345,18	330,54	345,24	273,66	150,12	240,3	210,36
21	60,36	60,48	90,18	270,24	210,84	345,18	330,66	345,06	180,72	120,42	91,44	210,24
22	90,36	30,42	150,54	300,3	330,42	345,12	345,18	345,18	120,42	150,24	181,62	270,18
23	150,9	30,6	300,3	210,36	344,52	240,72	300,3	345,12	120,36	120,54	0,18	150,18
24	330,24	150,24	210,24	330,36	341,7	330,54	330,6	345,06	330,48	120,36	0,12	150,48
25	90,3	90,42	210,24	240,78	280,74	330,6	345,18	300,72	330,6	180,3	150,18	150,18
26	91,2	240,96	90,24	330,54	218,94	330,24	345,24	300,54	330,18	120,24	180,36	90,96
27	210,42	120,78	300,3	300,96	270,06	334,86	345,18	210,78	345,06	120,3	91,14	90,36
28	30,78	240,12	345,06	344,94	240,9	330,3	344,4	211,02	180,9	90,54	90,3	150,6
29	0	0	300,78	344,94	240,72	330,18	330,42	210,78	60,36	90,24	181,08	150,3
30	120,12	0	330,24	345	330,18	330,3	210,78	210,9	150,48	120,36	210,24	180,18
31	0	0	270,6	0	343,14	0	150,78	90,24	0	270,72	0	0,96

Figure 42: Hammermill maximum working minutes with battery

Figure 42 shows the possible working hours of the hammer mill, there is a significant difference from the current situation shown in Figure 41. In the current situation, the maximum production is 16,45% of the total generated power. However, if the battery is added to the system, the maximum production will increase to 58,09%. This means that there is 6,452 MWh extra for the hammermill, or more meal could be produced.



Graph 10: Extra maze meal that could be produced in case with battery

Year	Max production meal without battery [kg]	Max production meal with battery [kg]
2018	70.500	288.500
2019	88.491	295.958
Average	79.495	292.229

Figure 43: Maximum production of meal compared with system with battery

Year	Days hammermill can’t work without battery	Days hammermill can’t work with battery
2018	212	16
2019	228	14
Average	220	15

Figure 44: The days the hammermill can't work, compared with battery

In Figure 43 and Figure 44, are the results of the calculations. It's concluded that the system with battery has a huge impact on the overall system performance.

Another option to improve the overall performance is to add and install more solar panels. Installing additional panels will increase the total power output. Where shortages can be eliminated. It may be cheaper to install additional panels than to install a battery. More research needs to be conducted here. However, we recommend using power optimizers that support MPP tracking, as explained in the theory section before.

11 CASE 2: University of Zambia

The data are divided into two different case studies. Both case studies are in rural areas of Zambia. CASE 2 is the study for UNZA (University of Zambia). The system consists of 4 batteries and 50 solar panels. These are divided into substrings. We don't have any information about the installed inverter, bypass diodes, or possible optimizers. So, we assume a basic system without MPPT tracking or any additional features that might improve the overall system performance. The system specifications are given in 11.1 System specifications .

During the dry season (mid-August to mid-November) in Zambia, the 50 solar panels are used to power the hammermill. However, during the rainy season, 20 panels are removed by the REA. The 4 batteries are only used during the rainy season (May to mid-August) to work with the 20 solar panels that power the connected households.

The whole system is located next to Kampekete Primary School in Chalimbana, Chongwe as shown in Figure 45, the coordinates are 15°23'39.0"S 28°45'56.6"E. Unfortunately, the picture is not up to date to see the solar system.

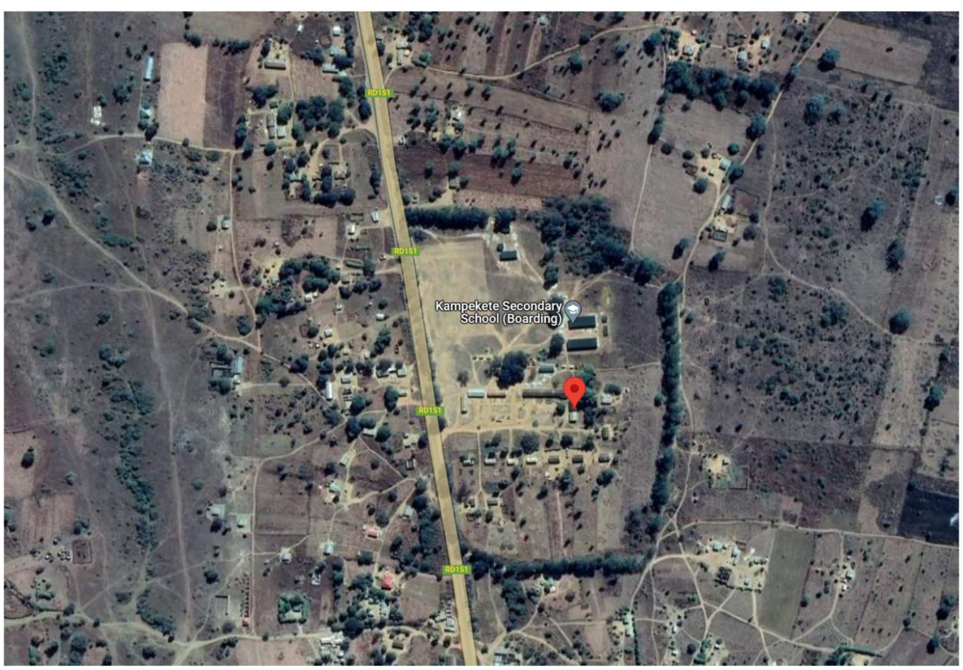


Figure 45: Google maps geographical photo UNZA case study

11.1 System specifications CASE2

11.1.1 Solar PV

Poly 156P60-250W[6]	
Cell Type	Polycrystalline
Cell Size	156×156 mm
Panel Dimension (H/W/D)	1640x992x40 mm
Maximum System Voltage	1000 V
Temperature	45±2 °C
Inclination	15 °
Maximum Power (Pmax)	250 Wp
Voltage at Maximum Power (Vmpp)	30.4 V
Current at Maximum Power (Impp)	8.23 A
Open Circuit Voltage (Voc)	37.7 V
Short Circuit Current (Isc)	8.79 A
Panel Efficiency	15.29 %
Power Tolerance (Positive)	+2%
Operating Temperature Range	40~80 °C
Temperature Coefficient of Pmax	0.47 %/°C
Temperature Coefficient of Voc	0.33 %/°C
Temperature Coefficient of Isc	0.04 %/°C

Figure 46: Picture of the solar panel

[6] ENF Ltd. (n.d.). Datasheet Poly 156-60. Retrieved April 28, 2023, from https://www.enfsolar.com/pv/panel-datasheet/crystalline/22685

11.1.2 Battery

LG Chem RESU 6.5 - 48V lithium-ion[7]	
Total Energy	6,5 kWh
Usable Energy	5,9 kWh
Capacity	126 Ah
Nominal Voltage	51,8 V
Voltage Range	42,0~58,8 V
Round-trip Efficiency	>95%
Max Power	4,2 kW
Peak Power (for 3 sec.)	4,6 kW
Dimension [W x H x D, mm]	452 x 656 x 120
Operational Temperature	-10~45 °C
Warranty	60% @10 years (Global)

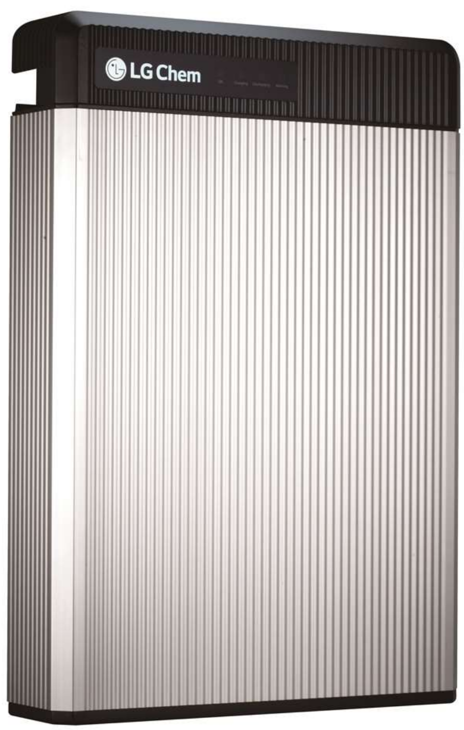


Figure 47: Picture of the battery

[7] Europe-solarstore. (n.d.). LG Chem RESU 6.5—48V lithium-ion storage battery. Retrieved May 5, 2023, from https://www.europe-solarstore.com/lg-chem-resu-6-5-48v-lithium-ion-storage-battery.html

11.1.3 Hammermill

Solar Powered Milling Machine[8]	
Model NO.	CCS-M 18081367
Voltage	48 V DC
Power rating	6,9 kW
Press Materials	/
Trademark	BMFSMO
Efficiency	85-90 %
Length of cycle	8 min

11.2 System configuration

With 50 solar panels installed, the system has a total maximum output of 12,5 kWp. The system also includes 4 batteries with a total energy storage capacity of 23.9 kWh. It's important to note that the batteries are only used during the rainy season for household or mini grid use.

During the dry season, an amount of 1,500 kg of maze meal is produced per day. Production during the dry season is from 7:00AM to 5:00PM. However, during the rainy season, the daily production is much lower, around 200 kg of maze meal per day. And the production schedule here is from 8:30AM to 3:30PM. This is because during the rainy season there is much more cloud cover and alternating irradiation from the sun.

[8] Data retrieved from Excel sheet UNZA

11.3 Analyzes

The analyses will follow the same reasoning as the Copperbelt University case study. This will facilitate the subsequent comparison of the two systems.

11.3.1 Study of the system from an energy point of view

First, the amount of energy not used by the system is examined. The simulations conducted for the years 2017, 2018 and 2019 give the results shown in Figure 48.

PEAK SHAVING POSSIBILITIES					
OVER PRODUCTION PERCENTAGE 2017:	1.56%	PRODUCTION 2017:	15226	OVER PRODUCTION 2017:	237
OVER PRODUCTION PERCENTAGE 2018:	1.07%	PRODUCTION 2018:	15124	OVER PRODUCTION 2018:	163
OVER PRODUCTION PERCENTAGE 2019:	1.31%	PRODUCTION 2019:	15277	OVER PRODUCTION 2019:	200
OVER PRODUCTION PERCENTAGE AVG:	1.31%	PRODUCTION AVG:	15209	OVER PRODUCTION AVG:	200

Figure 48: Calculated consumption and production profile

First, we can see in Figure 48 that the total energy production for one year is 15,209 kWh on average. This production is stable over the three years studied (+- 85 kWh), which corresponds to a relative variation of 0.5% if the average production over one year is taken as a reference. Of this energy produced, an average of 200 kWh is consumed by the hammer mill, leaving an average of 15,009 kWh unused over the three years, i.e., 98.69% of the total energy produced by the system over one year.
A significant amount of energy is therefore wasted. To give an idea of what this represents, the average annual electricity consumption of a French household is around 4,500 kWh, which means that 14,000 kWh represents more than three years of electricity consumption for an average household in France.

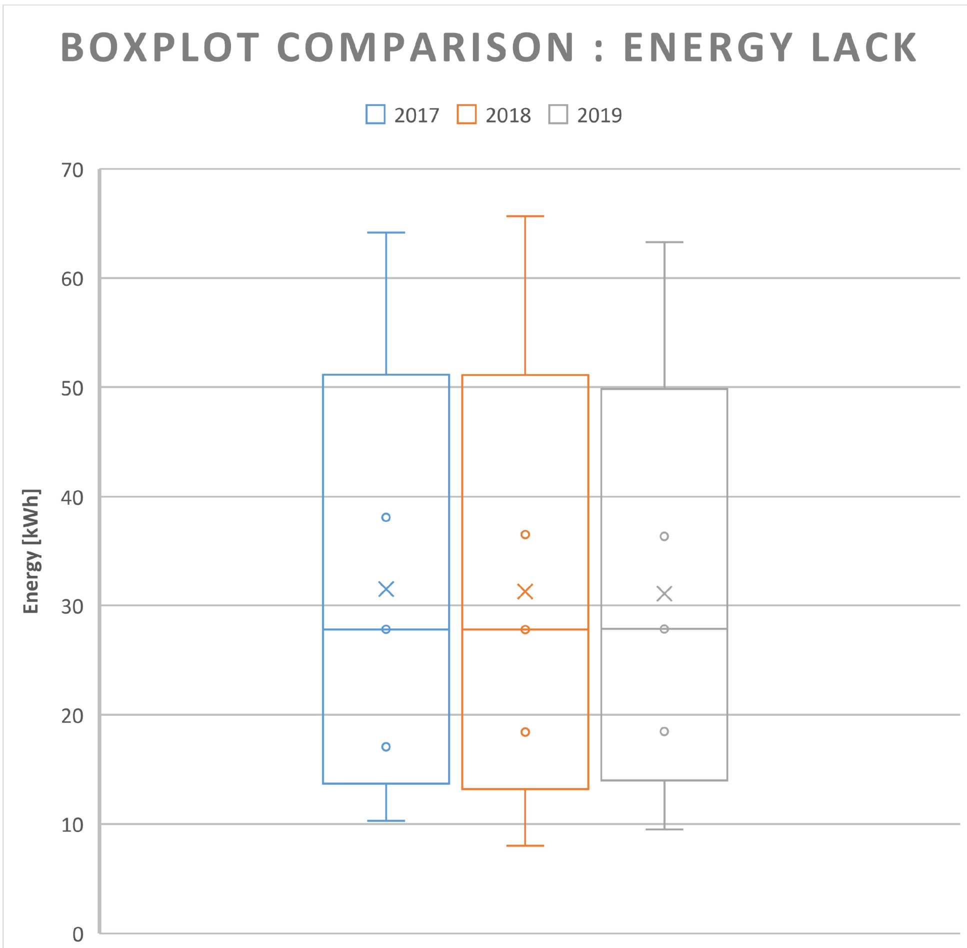
Another important aspect is the distribution of electricity production during the operating hours of the hammer mill. In fact, it is necessary to know whether this amount of energy is due to the fact that the system as a whole is undersized (most of the energy produced is wasted when the hammer mill is not running) or oversized (most of the energy produced is wasted when the hammer mill is running).

Year	Energy over produce (kWh) (not in work hour)	Energy over produce(kWh) (HM lack power)	Energy over produce(kWh) (HM is running)
2017	336.35	11941.86	2947.88
2018	348.98	12608.58	2165.97
2019	361.64	12743.46	2375.46
Average	348.99	12431.30	2496.44

Figure 49: Energy overproduction

From Figure 49: Energy overproduction The amount of excess energy produced when the hammer mill is in operation is relatively large, representing 16% of total electricity production. However, it remains insignificant in global terms when compared to the amount of energy wasted when solar panel production is insufficient to run the hammer mill, which represents 81% of total electricity production. The causes of this 81% could be an undersized system, an inappropriate time slot given the daily production of solar panels, or a combination of both.

For this purpose, it is interesting to study the distribution of the missing energy when the hammer mill is in its operating time slot. Indeed, if the majority of the missing energy is distributed around high values (compared to the hammer mill consumption), this tends to reflect time slot problems, while the values distributed around lower values reflect sizing problems.



Graph 11: Boxplot comparison energy lack

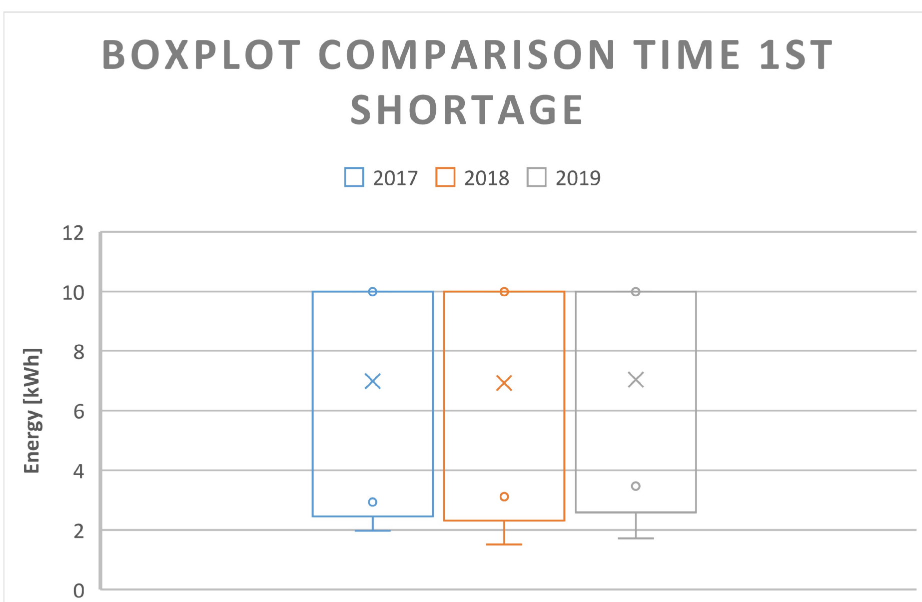
According to Graph 11, which compares several box plots, the box plots have globally the same 'spread' and similar medians (less than 1kWh difference), indicating a similar spread of missing energy over the three years. The extreme values are also similar (less than 4kWh difference). Thus, the annual climatic variability does not seem to have a large influence (according to this data set) on the missing energy for the operation of the hammer mill.

In addition to this aspect, Graph 11 also shows that in 50% of the cases the missing energy to operate the hammer mill is greater than approximately 28 kWh.

In conclusion, it is necessary to pay attention to the time slots as they can significantly change the results obtained. In any case, the operating times are not affected if it is assumed that the operating times are concentrated at the peak of electricity production. The analysis of the graphs clearly shows that significant improvements are needed to optimize the performance of the photovoltaic system to power the hammer mill efficiently and sustainably. It is essential that measures are taken to reduce energy wastage, maximize the use of the energy produced and ensure a stable energy supply for the hammer mill.

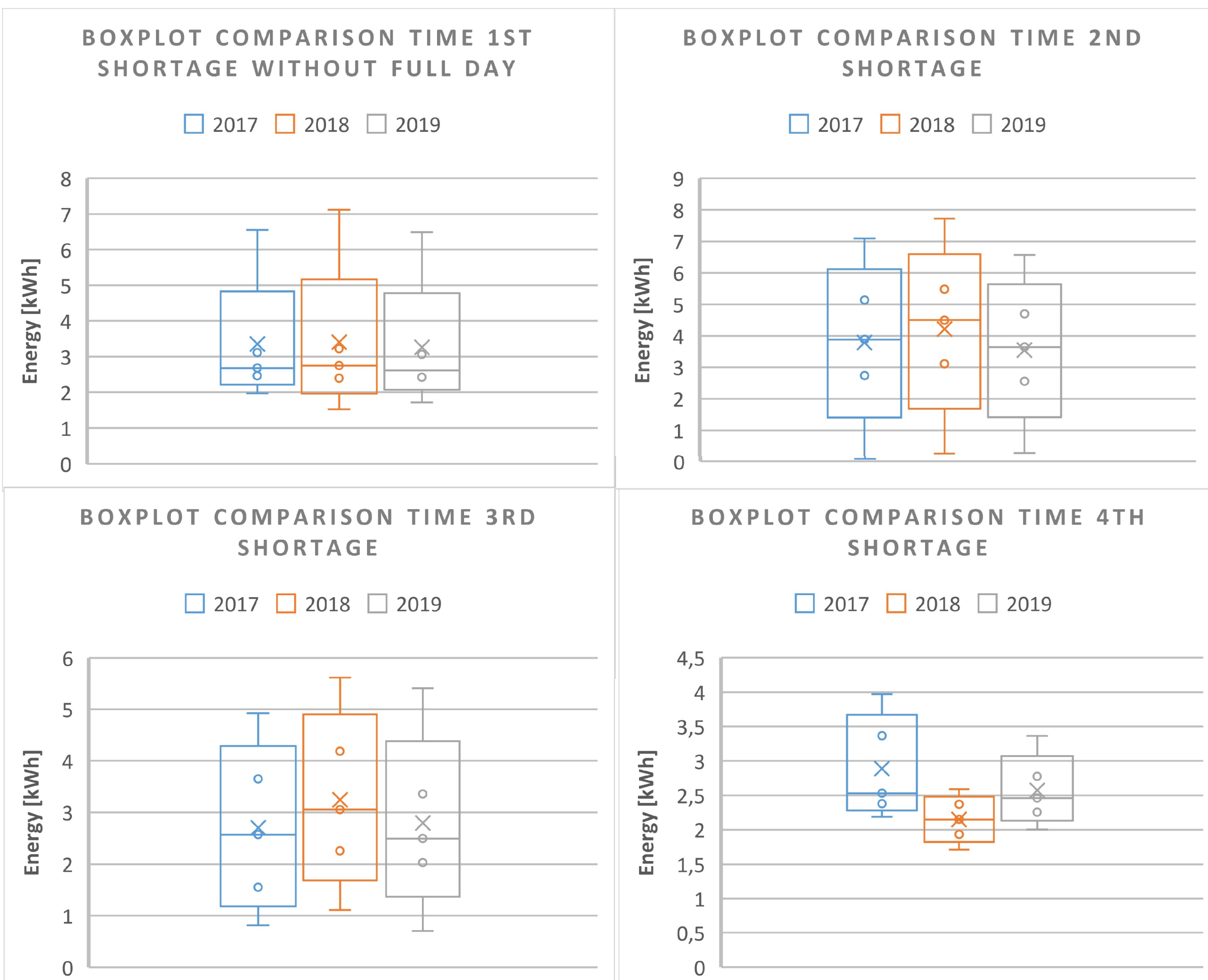
11.3.2 Study of the system from the user's point of view

The main objective of the system is to ensure maximum availability to operate the hammer mill when the local population needs it. The concepts of availability and the number and duration of breakdowns are therefore important. To this end, a comparison of the distribution of the duration of breakdowns by number over three years is presented below.



Graph 12: Boxplot time 1ste shortage

The median is confused with the third quartile, which in turn is confused with the maximum value (which corresponds to 10 H, working hours of the hammer mill) for the three years. This observation underlines the fact that more than half of the first cuts correspond to days when the hammer mill is not sufficiently supplied to operate. These box plots also highlight the fact that the duration of the first cut is between 0 and 10 hours. In particular, it can be seen that 75% of the first cuts are longer than 2.2 hours. It has been decided to follow the box plots for the first cut without considering the days when the hammer mill simply cannot work. In this way we remove the "parasitic" values that have shifted the corresponding values of our medians and quartiles. It is now possible to see in Graph 13 that the median time for the first cut was around 2.8 hours for 2017, 2018 and 2019.



Graph 13: comparison of the 4 boxplots'

Regarding the second denominations, on the left, the median for the 3 years is above the 4 h. In the graph on the right, third shortage, it’s possible to observe that the median is located around 2.8 hours.

Overall, we can conclude from this analysis that although the number of breakdowns is not very high, with a minimum of 1 per day and a maximum of 4, their duration is significant, as shown by the positioning of the medians. In fact, we can say that half of the interruptions last more than 2 hours. Therefore, depending on the year and the use of the hammer, the user can have a significant negative impact by being exposed to cuts that last more than a third of the time in half of the cases.

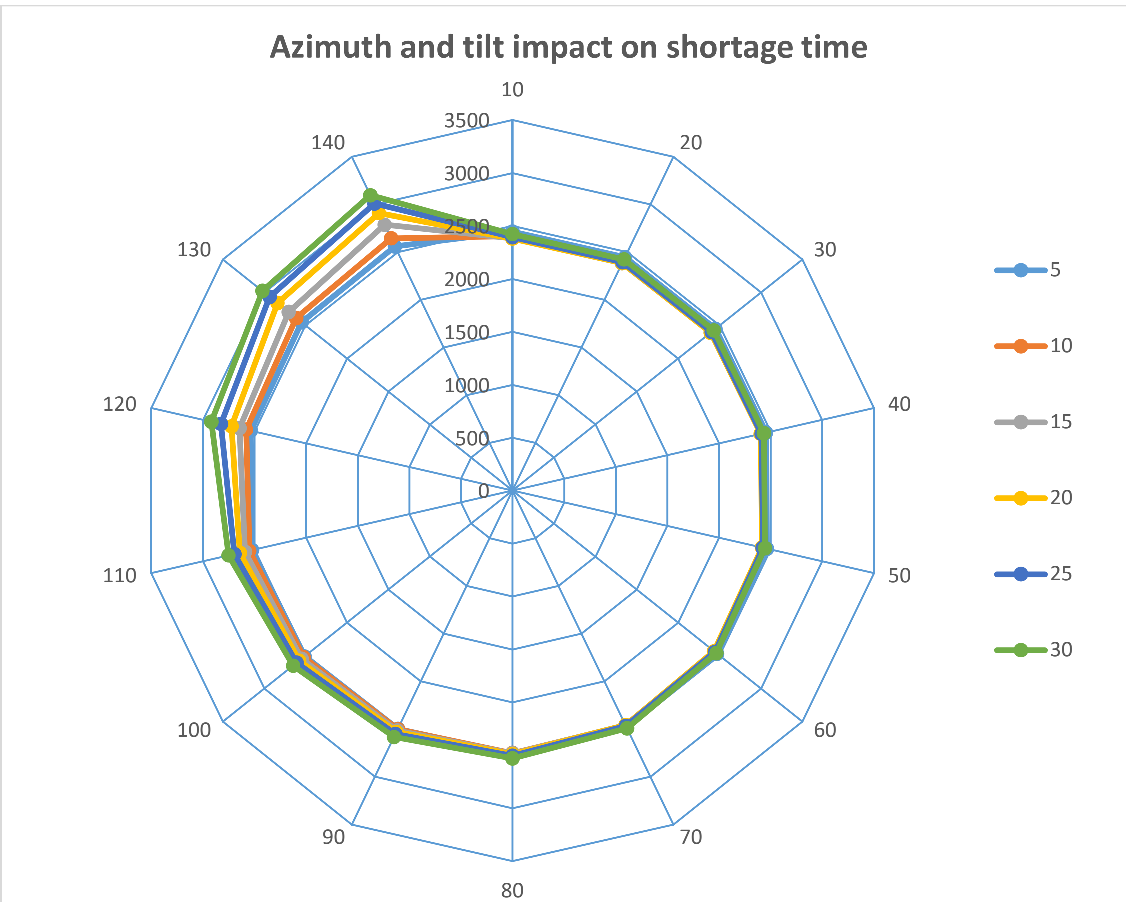
	January	February	March	April	May	June	July	August	Septembe	October	November	December
1	0	52.44	0	63.36	195.72	148.5	130.98	285.18	196.02	133.68	132.6	0
2	0	0	0	75.12	276.12	0	17.88	0	259.62	0	83.76	0
3	0	0	0	261.6	25.38	184.02	0	251.1	302.58	0	0	0
4	0	0	0	16.2	166.26	95.64	262.38	102.66	288.3	0	97.26	0
5	0	0	0	0	212.7	160.38	201.48	0	164.7	0	95.16	0
6	0	0	0	13.2	212.82	269.64	253.38	47.52	0	0	0	0
7	0	0	27.54	136.8	183.3	188.34	168.36	285.24	75.6	0	0	0
8	0	0	83.88	0	114.96	0	219.06	331.86	0	0	0	0
9	0	0	0	185.7	178.32	263.94	182.52	254.52	0	0	0	0
10	0	0	0	204.78	223.56	202.98	0	194.82	0	0	0	0
11	0	0	0	122.52	48.6	98.1	0	232.26	0	0	0	0
12	0	0	0	92.34	0	108.12	246.78	169.32	110.16	0	0	0
13	0	0	0	0	68.58	0	251.58	160.26	0	94.08	0	0
14	0	0	11.58	0	0	0	271.74	210.96	0	241.98	0	0
15	0	0	50.1	0	0	0	58.02	215.58	0	0	0	0
16	0	0	0	48.66	0	140.4	0	0	0	0	0	0
17	0	0	251.82	48.24	0	273.06	0	0	0	0	0	0
18	0	0	180.48	0	0	49.26	258.96	0	67.44	0	0	0
19	0	0	197.16	38.7	270.12	290.22	132.54	0	0	0	0	0
20	0	0	45.6	46.2	281.22	203.88	0	313.86	0	0	0	0
21	0	0	136.56	29.28	43.92	105.48	268.62	317.04	146.76	0	0	0
22	0	0	0	106.56	151.8	71.04	84.3	0	0	0	0	0
23	0	0	0	0	85.5	0	0	0	0	0	0	0
24	0	9.6	0	0	0	282.18	272.76	0	189.96	0	0	0
25	0	0	0	0	0	289.8	295.32	0	0	0	0	0
26	0	0	52.38	0	0	294.96	158.58	219.48	0	0	0	0
27	0	0	120.54	0	0	0	323.28	269.64	0	0	0	0
28	0	8.28	275.94	0	0	0	0	323.46	9.06	0	43.86	0
29	0		222.72	286.32	226.68	162.36	64.62	298.26	37.2	0	0	0
30	0		349.44	185.82	161.4	179.88	24.84	77.04	62.04	0	0	0
31	0		80.16		0		269.64	283.32		170.64		0

Figure 50: Maximum amount of minutes the hammermill can operate

If we look at Figure 50, the year 2017 as an example, we see that the availability of the hammer mill is heterogeneous. Especially during the rainy season, the number of days that the hammer mill can operate is severely limited. For example, according to our simulations, the hammer mill could not operate during the months of December and January, whereas it could operate for 21 days during the month of August. This heterogeneity, combined with the long periods of use, makes the hammer mill almost impossible to use in practice.

Another point of view can be taken from the system itself. First, it should be emphasized that the data we have is partial. The same comments can be made here as for the Copperbelt University case study. Our exchanges with our Zambian partners seem to confirm the absence of MPP tracking and DC optimizer in the system.

The configuration of the system (inclination and azimuth) must also be evaluated if you want to get the most out of the system. In fact, in our case, the optimal configuration is not necessarily the one that produces the most electricity per year. It corresponds to the one that is most likely to reduce the power outage time. Graph 14 shows the average annual shortage time in hours (for the year 2017) as a function of the azimuth (10 to 140°) and the tilt of the solar panels (5 to 30°).



Graph 14: System Performance Related to Positioning

In Graph 14, an increase in both tilt and azimuth independently results in an increase in downtime. After comparing the possible configurations, the current configuration of the system (Azimuth = 0°) and Inclination 15° is the optimal configuration, which allows to reduce the downtime as much as possible.

Note that all the previous results were obtained with the system in summer configuration, i.e. using 50 solar panels. The configuration used during the rainy season, with 30 solar panels, did not give any interesting results (the hammer mill is never in operation).

In conclusion, these results highlight the need to take measures to improve the energy efficiency and energy management of the system. This could include the use of more efficient technologies, the installation of an energy storage system.

11.4 Calculations

Before removal of solar panels:

$PROFIT = C_{kg} \cdot Prod$ [K/day]

$Prod_{hourly} = \frac{Prod}{t_{day}}$ [kg/h]

$PROFIT_{hourly} = Prod_{hourly} \cdot C_{kg}$ [K/h]

$E_{day} = \frac{P_{system} \cdot t_{day}}{1000}$ [kWh/day]

$Indicator = \frac{E_{day}}{Prod}$ [kWh/kg]

$E_{bag} = Indicator \cdot W_{bag}$ [kWh/bag]

Where:

$PROFIT$ - Daily profit

$Prod_{hourly}$ - Average hourly production ;

$PROFIT_{hourly}$ - Profit per hour ;

E_{day} -Energy consumption per day ;

$Indicator$ -Indicator ;

E_{bag} -Energy consumption per bag ;

Numerical results :

$PROFIT = 0{,}48 \cdot 1500 = 720$ [K/day]

$Prod_{hourly} = \frac{1500}{10} = 150$ [kg/h]

$PROFIT_{hourly} = 150 \ \cdot 0{,}48 = 72$ [K/h]

$E_{day} = \frac{6900 \cdot 10}{1000} = 69$ [kWh/day]

$Indicator = \frac{69}{1500} = 0{,}05$ [kWh/kg]

$E_{bag} = 0{,}05 \cdot 50 = 2$ [kWh/bag]

The hypothesis after removal of solar panels:

$$t_{day} = 7\ h/day$$

$$P_{system} = 6900W$$

$$C_{kg} = 0{,}48\ K/day$$

$$Prod = 200\ kg/day$$

$$W_{bag} = 50\ kg$$

Numerical results:

$PROFIT = 0{,}48 \cdot 200 = 96$ [K/day]

$Prod_{hourl} \ = \frac{200}{7} = 28{,}57$ [kg/h]

$PROFIT_{hou} \quad = 28{,}57 \cdot 0{,}48 = 48{,}3$ [K/h]

$E_{day} = \frac{6900 \cdot 7}{1000} = 48{,}3$ [kWh/day]

$Indicator = \frac{48{,}3}{200} = 0{,}2415$ [kWh/kg]

$E_{bag} = 0{,}24 \cdot 50 = 12{,}075$ [kWh/bag]

	Average hourly production [kg/h]	energy consumption indicator [kWh/kg]	profit per hour[K/h]	profit per day [K/day]
Before removal of solar panels:	150	0.046	72	720
After removal of solar panels:	28.57142857	0.2415	13.71428571	96

The capacity of Hammer mill photovoltaic panels and the potential revenue from this system are calculated above. Another important aspect is we take into consideration 2 scenarios, first one is with 50 solar panels, and the second scenario is with 20 solar panels removed. Due to the rainy season, 20 solar panels had to be removed because the households were no longer connected to the mini grid.

In the hypotheses, it is known that the hammer mill has a power rating of 6900 W, that the solar panels work for a total of 10 hours each day during the dry season to produce 1500 kg of maze and solar panels work for a total of 7 hours each day to produce 200 kg of maze during the rainy season.

According to the table, profit per hour is 5 times more in the dry season than it is in the rainy season. Because there is less production of maze during the rainy season, the energy consumption indication is also five times more than it is during the dry season. The maximum profit per day during dry season is considerable with 720 K/day (K=kwacha currency in Zambia) around 36 euro at exchange rate from 05.05.2023. This indicator is very important to take into consideration the next investment for the system.

11.4.1 Householder cases:

In this following part is calculated the maximum number of subscription that the system could feed if is used just the battery storage for 1 day

The lack of dataloggers prevents an advanced computation from being made that would be more accurate; instead, the statistics will be more for a better understanding of how the system can work.

The scenario that will be used it's the cleanest one when all the householders are connected to the mini grid during the subscription time without any fluctuations:

- TV and 1 bulb (14pm to 24pm);
- 1 bulb (17pm to 5am);

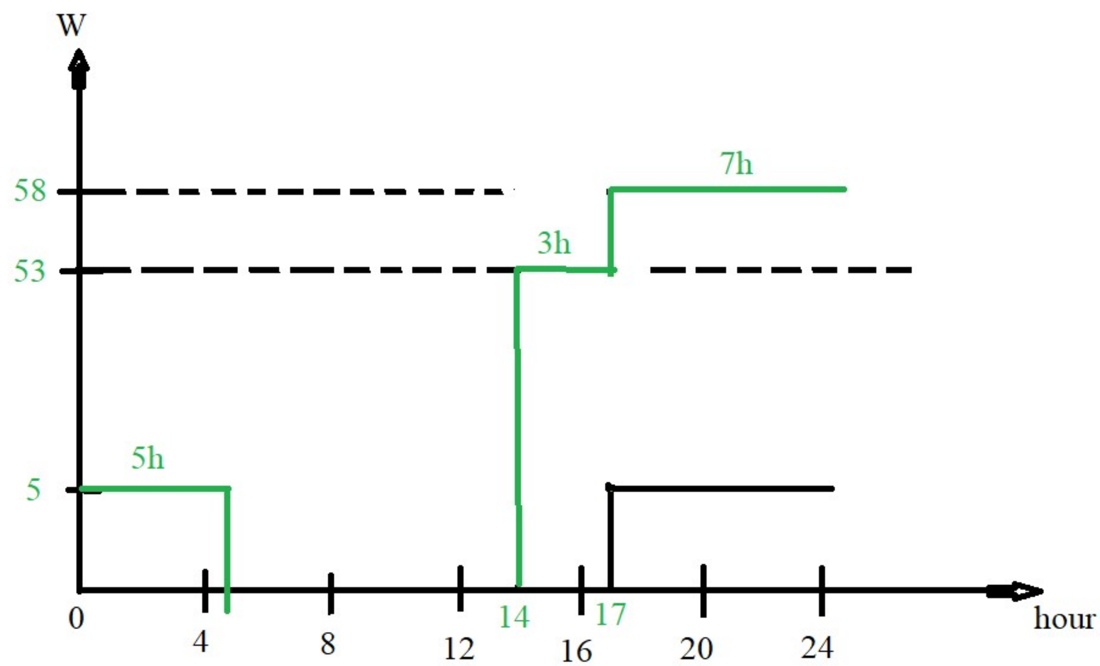


Figure 51: Householders consumption graph

The following equations can extract:

I: $x \cdot n_h \cdot c_1$

II: $y \cdot n_h \cdot c_2$

III: $(x \cdot c_1 + y \cdot c_2) \cdot n_h$

Where:

- x - number of householders that have subscription for 1 bulb with 5 W
- y – number of householders that have subscription for 1 bulb + 1 TV set with 53W
- nh – number of hours with one of the subscriptions
- c1 – maximum consumption of householder with subscription of 5W
- c2 - maximum consumption of householder with subscription of 53W

After inputting the values will obtain:

I: $x \cdot 5 \cdot 5$

II: $y \cdot 5 \cdot 53$

III: $(x \cdot 5 + y \cdot 53) \cdot 7$

From the graph the following information could be extracted:

- Between 00:00 – 05:00 – the consumption is maximum 5W/ householder
- Between 14:00 – 17:00 – the consumption is maximum 53W/householder
- Between 17:00 – 00:00 – both subscriptions could be used in the same time period, so the maximum consumption is 58 W

In the next calculation it's to define how many householders from each subscription could be feed during 24h using our batter system - 26 kWh capacity

To obtain this result, it's necessary to make a sum with all period of consumption I; II; III and to equal with battery capacity, but it's important to take in consideration that the maximum discharge level of the battery could be 20%

$$I + II + III = 26000 \cdot 0.8$$

$$25x + 159y + 35x + 371y = 20800$$

$$60x + 530y = 20800$$

In order to solve this problem, it's necessary a second equation. The total number of householders are known 72 and it will follow:

$$x + y = 72$$

$$60x + 530y = 20800$$

By solving this equation, the results will be next:

$$x = 36.93$$

$$y = 35.05$$

But it needs an integers number, and y couldn't by high than 35.05 so the final results will be.

$$x = 37$$

$$y = 35$$

In conclusion, during a normal day with a battery that is fully charging from the sunrise until 2PM the maximum subscription with 1TV+1bulb that the battery system could feed is 35. There couldn't be more that this value because that means all other householders will be out of electricity. Using these values, it's easy to understand that the grid could be extended for subscription with 1 bulb, but it's necessary to lower the number of subscription 1 TV + 1 bulb to a certain number lower than 35.

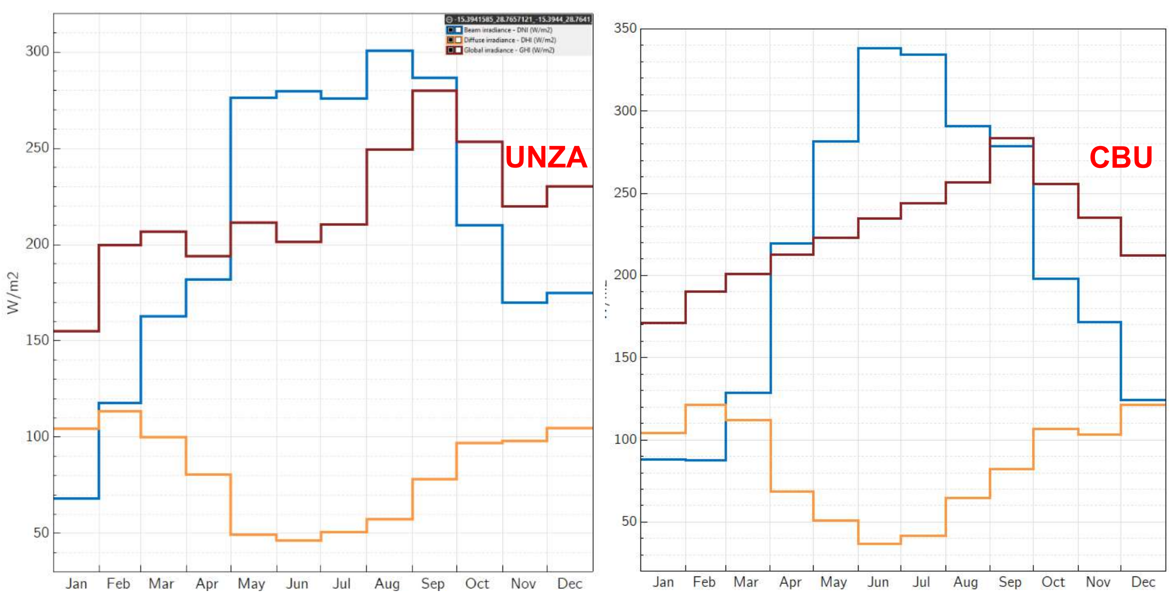
Due to lack of information about invertor and dataloggers this calculation can't take into consideration another profile of the consumption. There will never be a moment when all householders are connected to maximum capacity.

12 Case 1 & case 2: comparison

With over 2000 similar systems currently in operation in the country, it is important to understand and learn from the differences between these two case studies to improve the design and implementation of similar systems.

Firstly, in terms of the systems themselves, the configuration adopted is similar. Namely, the use of a hammer mill with a power of 7kW and 6.9kW respectively for cases 1 and 2, powered directly by the electricity produced by the solar panels. While the first case uses 255W modules, the second uses 250W modules, bringing the power of the systems to 12.75kW and 12.5kW respectively.

If we compare the two systems from an energy point of view, we can see that the percentage of electricity produced that is used is not suitable: 14% and 2% respectively for cases 1 and 2. This first significant difference between two similar systems can be partly explained by the all-or-nothing consumption of the hammer mill. In fact, sometimes only a few watts of production are missing to start the hammer mill and therefore this energy is "used". Another explanation lies in the climatic conditions. As explained earlier, Zambia is a huge country and the climates encountered locally can sometimes vary significantly. For example, if we look at the year 2017, the monthly irradiance profiles are as follows:



Graph 15: Irradiation graph compared

Graph 15 shows that the contribution of incident and diffuse radiation to the total irradiance is not equal. Furthermore, if we look at the month of July, for example, we see a difference of 60 W/m² between the two cases. This variability must be considered when sizing the system to ensure that the system produces enough. In addition to these aspects, we can also see that the habits on site are not the same, whereas during the dry season the hammer mill works for 6 hours in case 1, it works for 10 hours in the second case.

III Conclusion

13 Conclusion and discussion

In conclusion, our report has focused on the analysis, evaluation, and comparison of two solar-powered hammer mills in rural Zambia, with the aim of identifying areas for improvement. The report is divided into two main parts: the theoretical background and the modeling and analysis, which is the most important.

The theoretical part provides an overview of Zambia, hammer mills, photovoltaic systems, inverters, batteries, and maintenance of solar systems. This section is crucial in providing a theoretical foundation that is essential to understanding the performance of the two cases under consideration.

In the modeling and analysis part, we used the System Advisor Model (SAM) and a self-written Python program to analyze the behavior of the systems and calculate the production of electricity. We studied two cases: the University of Zambia and the Copperbelt University. The analysis of these cases from different perspectives, including the energy perspective, the user perspective, and the system perspective, showed that both systems were inefficient.

The energy perspective showed that there was a significant amount of energy that was not being used, and the energy produced when the hammer mill was operating was not significant. The user perspective showed that there were many power outages during the operation of the hammer mill, especially during the rainy season. The distribution of the hammer mill's operating hours was uneven throughout the year, which limited access to the hammer mill. From a system perspective, there was a lack of devices that could improve the capacity of the system, such as Maximum Power Point Tracking (MPPT) and DC optimizers.

A comparison of the two cases showed that they had similar inefficiencies. However, the size of Zambia and the variability of solar irradiance make it difficult to generalize our results to the 2000 other similar systems in Zambia. To improve the efficiency of the systems, we suggest the implementation of energy storage (batteries). The use of batteries significantly improved the efficiency of the Copperbelt University case by 40%. However, batteries are expensive, and it could also be interesting to add more solar panels to compensate for the lack of batteries. The use of batteries seems necessary to ensure the stability and availability of the hammer mill.

In conclusion, our study has shown that the solar-powered hammer mills in rural Zambia are inefficient and that there is a need to implement energy storage solutions, such as batteries, to improve their efficiency. The study has also highlighted the importance of theoretical background knowledge in understanding and improving the performance of solar-powered systems. Finally, we recommend further research to explore the potential of adding more solar panels as an alternative to batteries, and to investigate the feasibility of implementing MPPT and DC optimizers to improve the efficiency of the systems.

14 Appendix

14.1 Team presentation

The team is composed of three players from three different countries:

Hi, I'm Linus. I come from Antwerp Belgium, and I'm now in my last year of Bachelor in Energy Management at AP University of Applied Sciences. After completing my high school studies in electrical installation engineering, I was very interested in the energy

sector. My practical experiences allow me to apply my knowledge to the project in Zambia. EPS offers enormous opportunities in terms of development and international cooperation. And I am very honored to work on it with the international partners in Africa and with this amazing international team.

Hi, my name is Adrian and I'm coming from Romania, Valcea. Back home I study master's degree about renewable Energy at University Politehnica of Bucharest. I chose to pursue this project because I wanted to work on a genuine renewable energy project. I intend to apply my knowledge to this project in order to successfully fulfill our assignment.

My name is Nolann, I'm 22 years old, and I come from Brittany in France. In my home, I'm studying at ENIT (Ecole Nationale d'Ingénieurs de Tarbes), which is a generalist engineering school with a focus on mechanical engineering and industrial engineering. I have an option in building and public works. I decided to participate in EPS because I wanted to contribute to a useful project for society. This explains why I chose this project. Otherwise, I think that the learning approach by project is quite different than the classical method (course) and can help to fix knowledge more durably; it is also more rewarding and adds value to our academic career. Another important aspect for me concerns the multicultural work environment, which is very enriching.

14.2 Project management

14.2.1 Gantt chart and WBS

EPS not only exist of a project but there are some additional courses like Swedish, English and Project management to enhance our project during the semester.

First, the project management courses are given to improve the organization and the scheduling during the beginning of the semester. It raises the awareness about some "new" techniques of management such as SCRUM (the Agile method) to avoid being stuck in the traditional method, which may not be completely suited for an EPS project. We were thinking about the possibility of incorporating some elements of the agile method into the traditional one. [The different ways of reflection included the next one: structuring the teams around the work or the product, trying to include more stakeholders in the project to obtain more feedback. However, the project started with an open-minded spirit.

As a result, it was necessary to do basic research on our project to avoid mistakes. The best representative example of how to improve a project like an EPS project is to find SMART (Specific, Measurable, Assignable, Realistic and Time) goals. In this way, there is a clear understanding of what needs to be done, the search for uncertainties in the project, and the definition of the project's tasks and goals.

Figure 52: QR code WBS

Appendix

Subsequently, a Work Breakdown Structure (WBS) was developed for the project. The WBS is easy to read, but it's difficult to break it down into a simple basic task for a project. After defining the responsibility matrix (distribution of responsibilities for various tasks), consists of a team of three team members. Since the distribution of responsibilities is natural, the responsibility matrix is almost useless in this case.

Finally, the Gantt chart was created to follow up the weekly progress of the Project. This represents the period from the beginning of the course until completion of the group project. However, Gantt charts are the timed version of the Work Breakdown Structure. After planning the work packages, the WBS is visible on a time axis. This shows, for example, how long the package would take. Milestones are also included in the project (the midterm report, energy week in Vaasa, workshop, etc.). Furthermore, to keep a good rhythm and a consistent schedule, an extra fictive midterm report was added.

Figure 53: QR code Gantt diagram

Appendix

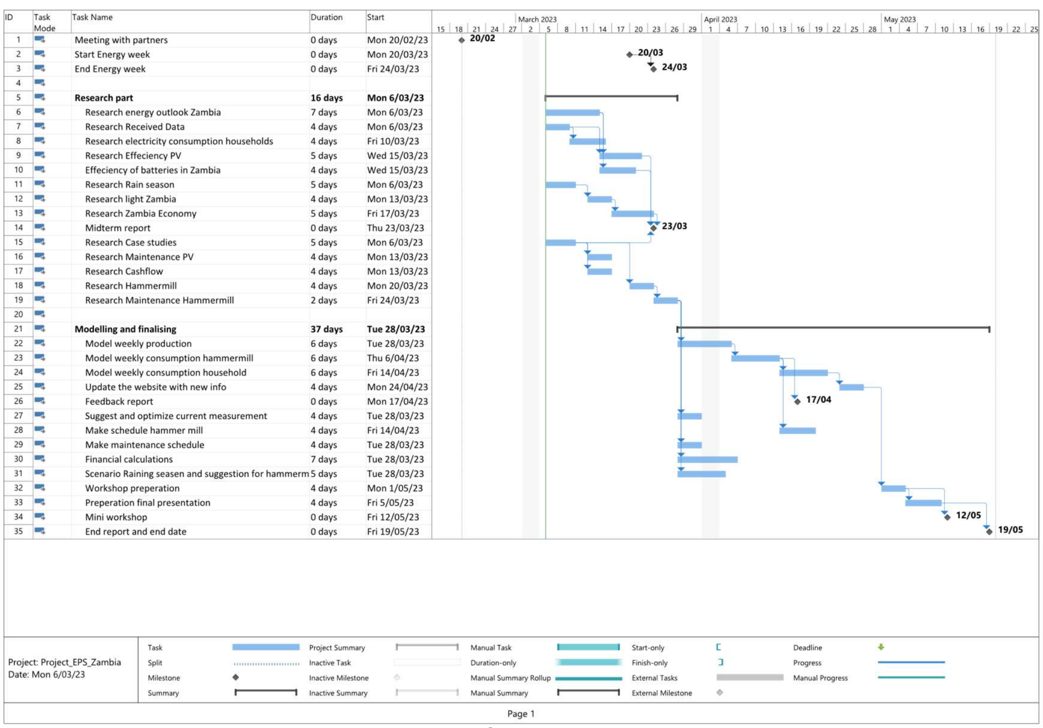


Figure 54: Gantt diagram

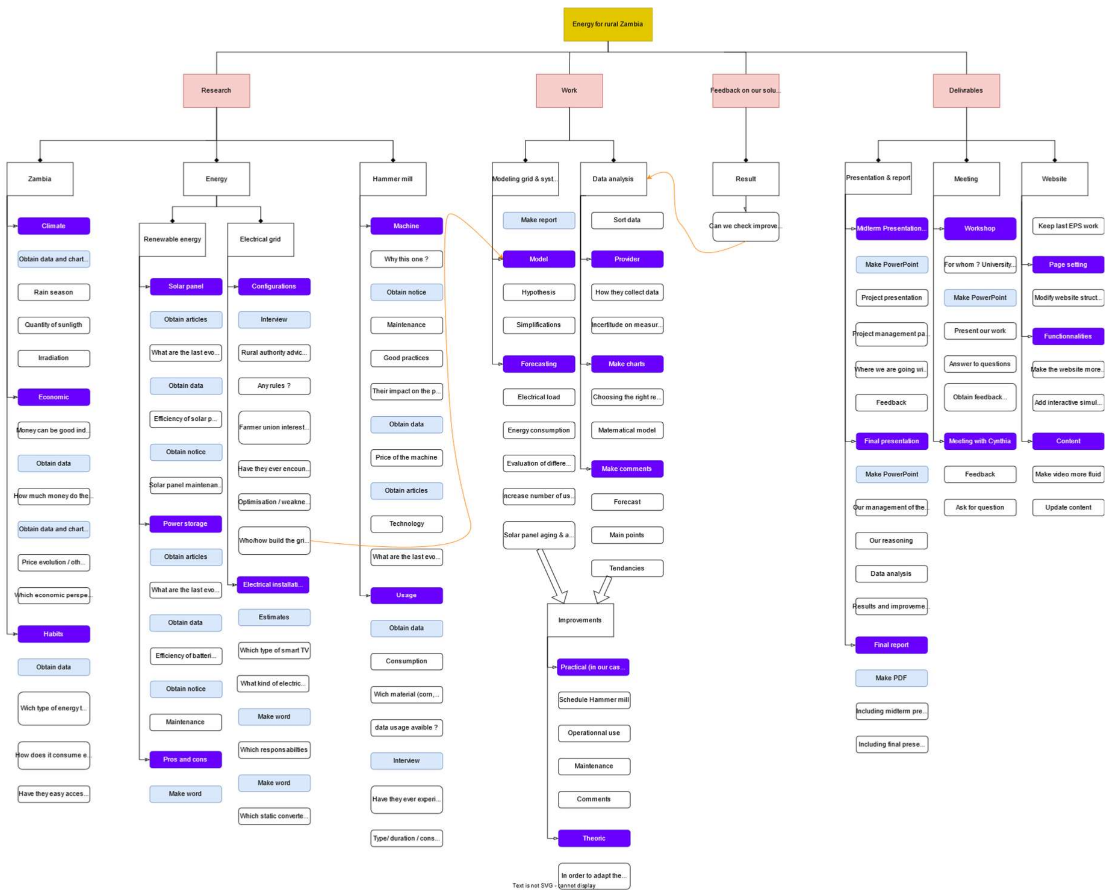


Figure 55: Efficiency calculations of the solar system

14.2.2 Belbin test

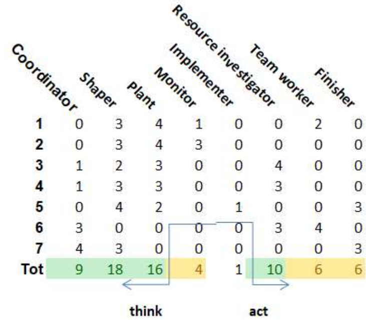
14.2.2.1 Individual result

Why: “Using the Belbin test can give people a greater understanding of their strengths, which leads to more effective communication in the team.”

“Managers” can enhance the performance of the team and ensure that everyone feels that they are making a difference in the workplace, which is very important if we want each one to be involved.

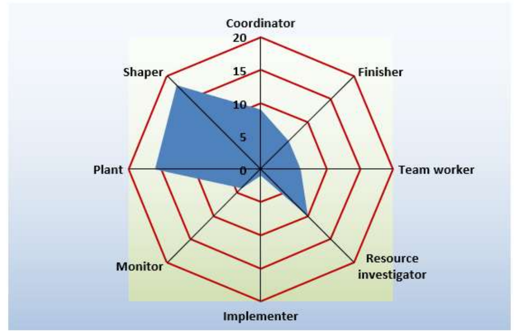
So, Belbin test (= behavioral test) must view like a practical tool to help individuals, teams and organizations work more effectively to achieve business objectives in allowing them to measure preference (express behavioral traits) from nine different Team Roles (but note that Team Roles are not equivalent to personality types). The Belbin scores people on how strongly they express behavioral traits. (“Team Role Inventories,” 2023; *The Nine Belbin Team Roles*, n.d.)

Nolann :



	Coordinator	Shaper	Plant	Monitor	Implementer	Resource investigator	Team worker	Finisher
1	0	3	4	1	0	0	2	0
2	0	3	4	3	0	0	0	0
3	1	2	3	0	0	4	0	0
4	1	3	3	0	0	3	0	0
5	0	4	2	0	1	0	0	3
6	3	0	0	0	0	3	4	0
7	4	3	0	0	0	0	0	3
Tot	9	18	16	4	1	10	6	6

think act

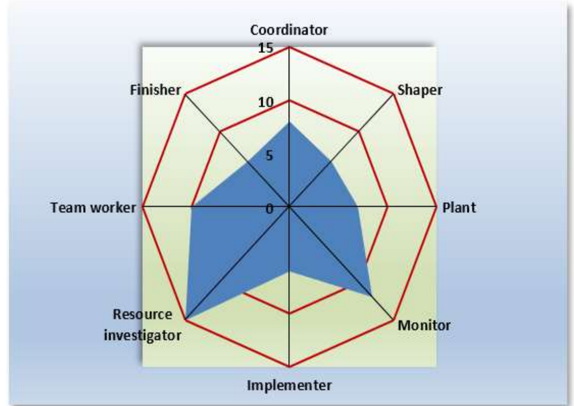


Role	Strengths	Allowable weaknesses	Don't be surprised to find that …
Shaper (25 %)	Challenging, dynamic, thrives on pressure. Has the drive and courage to overcome obstacles.	Can be prone to provocation, and may sometimes offend people's feelings.	They could risk becoming aggressive and bad-humoured in their attempts to get things done
Plant (23%)	Creative, imaginative, free-thinking, generates ideas and solves difficult problems.	Might ignore incidentals, and may be too preoccupied to communicate effectively.	They could be absent-minded or forgetful.
Ressource investigator (14%)	Outgoing, enthusiastic. Explores opportunities and develops contacts.	Might be over-optimistic, and can lose interest once the initial enthusiasm has passed.	They might forget to follow up on a lead.
Co-ordinator (13%)	Mature, confident, identifies talent. Clarifies goals.	Can be seen as manipulative and might offload their own share of the work.	They might over-delegate, leaving themselves little work to do.

Linus:

	Coordinator	Shaper	Plant	Monitor	Implementer	Resource investigator	Team worker	Finisher
1	0	1	1	2	0	3	2	1
2	0	2	1	1	0	3	3	0
3	2	0	1	3	1	2	1	0
4	1	0	2	1	3	1	2	0
5	0	0	2	2	1	2	0	3
6	2	2	0	1	1	2	2	0
7	3	1	0	2	0	2	0	2
Tot	8	6	7	12	6	15	10	6

think act

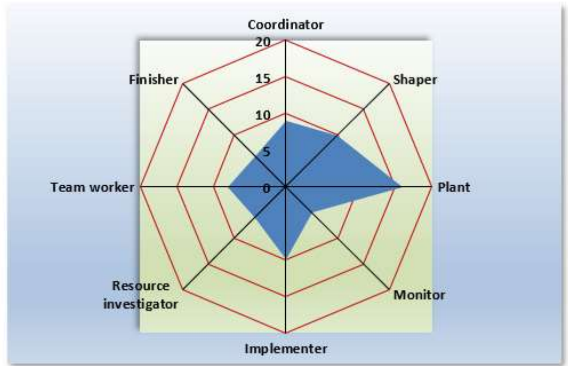


Role	Strengths	Allowable weaknesses	Don't be surprised to find that …
Ressource investigator (21%)	Outgoing, enthusiastic. Explores opportunities and develops contacts.	Might be over-optimistic, and can lose interest once the initial enthusiasm has passed.	They might forget to follow up on a lead.
Monitor Evaluator (17%)	Sober, strategic and discerning. Sees all options and judges accurately.	Sometimes lacks the drive and ability to inspire others and can be overly critical.	They could be slow to come to decisions.
Teamworker (14%)	Co-operative, perceptive and diplomatic. Listens and averts friction.	Can be indecisive in crunch situations and tends to avoid confrontation.	They might be hesitant to make unpopular decisions.

Adrian :

	Coordinator	Shaper	Plant	Monitor	Implementer	Resource investigator	Team worker	Finisher
1	0	0	3	0	2	3	2	0
2	0	0	4	0	2	2	1	1
3	2	2	0	1	0	0	1	4
4	1	0	2	3	0	0	3	1
5	1	4	3	0	2	0	0	0
6	1	1	3	1	2	1	1	0
7	4	3	1	0	2	0	0	0
Tot	9	10	16	5	10	6	8	6

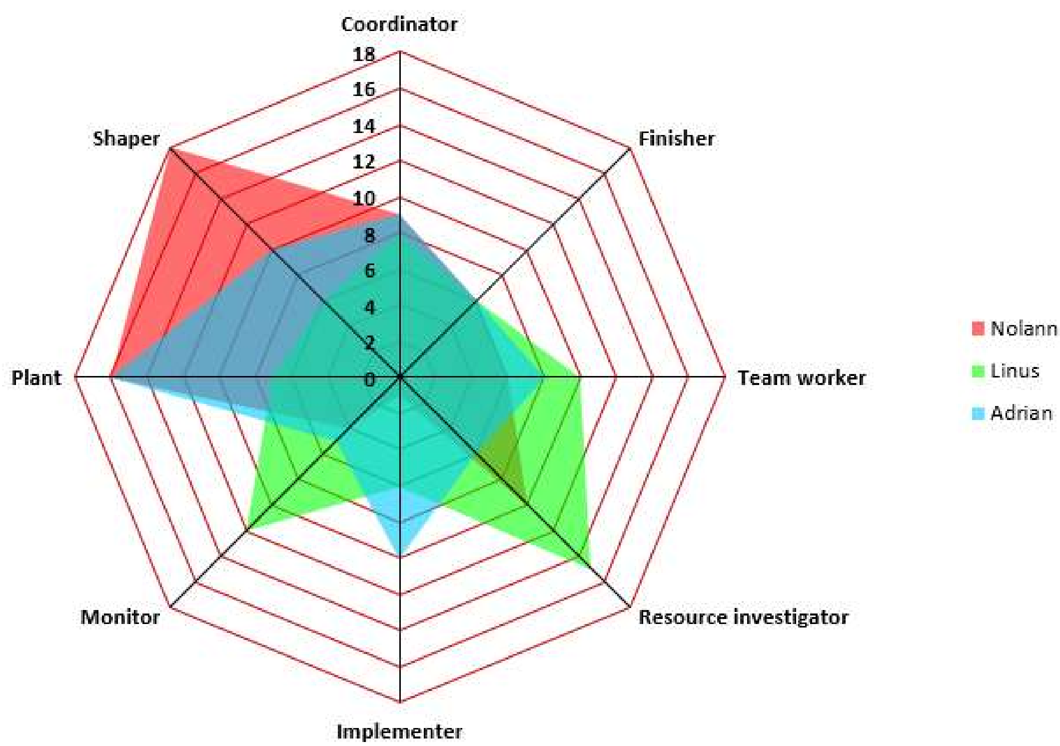
think act



Role	Strengths	Allowable weaknesses	Don't be surprised to find that …
Plant (23 %)	Creative, imaginative, free-thinking, generates ideas and solves difficult problems.	Might ignore incidentals, and may be too preoccupied to communicate effectively.	They could be absent-minded or forgetful.
Shaper (14%)	Challenging, dynamic, thrives on pressure. Has the drive and courage to overcome obstacles	Can be prone to provocation, and may sometimes offend people's feelings.	They could risk becoming aggressive and bad-humoured in their attempts to get things done.
Implementer (14%)	Practical, reliable, efficient. Turns ideas into actions and organises work that needs to be done.	Can be a bit inflexible and slow to respond to new possibilities.	They might be slow to relinquish their plans in favour of positive changes.
Co-ordinator (13%)	Mature, confident, identifies talent. Clarifies goals.	Can be seen as manipulative and might offload their own share of the work.	They might over-delegate, leaving themselves little work to do.

14.2.2.2 Team result

We can see two types of profiles emerge from the test: those with specialties and those who excel in multiple fields. While Adrian and Linus appear to have large profiles with strong tendencies towards multiple roles with one specialty, other profiles, such as Nolann's, show more specialization in certain fields off other fields, such as implementer. Linus and Adrian will probably be more polyvalent than Nolann. We also notice that Adrian and Nolann are more in thought and Linus is more in action. The compilation of results gives us the next graphic:



Graph 16: Team Belbin result

subjecting it to the highest standards of quality control.

Linus and Adrian also have profiles that complement each other well. However, Nolann and Adrian have the same plant profile, so at first glance there seems to be no conflict, just too many solutions. But their absent-minded tendencies and the fact that they can be too preoccupied can harm group communication. Finally other profiles like coordinator aren’t well contrasted between us.

15 References

Africa-political-map.jpg (JPEG Image, 1325 × 1600 pixels) – Scaled (40%). (n.d.). Retrieved April 19, 2023, from https://3.bp.blogspot.com/-IumDh_KtJjk/T4mzp71Ng5I/AAAAAAAACfg/_ZzT1dpwDxQ/s1600/africa-political-map.jpg

Altenenergytutorials. (2023, March 7). *Stand Alone PV System for Off-grid PV Solar Power*. Alternative Energy Tutorials. https://www.alternative-energy-tutorials.com/solar-power/stand-alone-pv-system.html

Anasjonahidrissi, Y. (2021, October 15). *Do Solar Panels Work In The Shade? A Complete Guide To Solar Panel Shading, Its Effect, And Its Solutions | RenewableWise*. https://www.renewablewise.com/do-solar-panels-work-in-the-shade/

Christensson, P. (2016, March 15). *Diode Definition*. https://techterms.com/definition/diode

De Rooij, D. (n.d.). *Short Circuit Current*. Retrieved May 3, 2023, from https://sinovoltaics.com/learning-center/basics/short-circuit-current/

De Winne, O. (2012, July 4). *Electriciteit uit zonlicht*. https://issuu.com/morriske/docs/solarlandscape

DualSun, M. (2023, March 17). *What is the difference between energy (kWh) and peak power (kWp)?* DualSun. https://academy.dualsun.com/hc/en-us/articles/360017363999-What-is-the-difference-between-energy-kWh-and-peak-power-kWp-

Durão, B., Torres, J. P., Fernandes, C., & Lameirinhas, R. (2020). Socio-economic Study to Improve the Electrical Sustainability of the North Tower of Instituto Superior Técnico. *Sustainability*, *12*, 1923. https://doi.org/10.3390/su12051923

Electrical4U. (2020, October 27). *What is Standalone Solar Electric System? | Electrical4U*. Https://Www.Electrical4u.Com/. https://www.electrical4u.com/what-is-standalone-solar-system/

energyaccess-africa. (2017, August 11). Electricity Access in Zambia. *Energy Access - Africa*. https://energyaccessafrika.wordpress.com/2017/08/11/electricity-access-in-zambia/

ENF Ltd. (n.d.). *Datasheet Poly 156-60*. Retrieved April 28, 2023, from https://www.enfsolar.com/pv/panel-datasheet/crystalline/22685

Flemish Energy Agency. (2013). *Elektriciteit uit zonlicht—Zonnepanelen—- PDF Free Download*. Adoc.Pub. https://adoc.pub/elektriciteit-uit-zonlicht-zonnepanelen-.html

FSP global. (2022, November 21). *Battery Energy Storage System: What Is It and How Does It Work?* http://www.fsp-group.com/en/knowledge-prd-54.html

Gerhardt, N. (2023, April 27). *The Ultimate Solar Panel Maintenance Guide To Keep Your Panels Working As Efficiently As Possible*. Forbes Home. https://www.forbes.com/home-improvement/solar/solar-panel-maintenance-tips/

Głogowski, P. (2022). *Battery Management System (BMS) | Solidstudio*. https://solidstudio.io/blog/battery-management-system-bms

Gobler, E. (2021). *Solar panel maintenance guide: How to clean and repair solar panels*. CNET. https://www.cnet.com/home/energy-and-utilities/solar-panel-maintenance-guide-how-to-clean-and-repair-solar-panels/

Guo, L., & Otieno, A. (n.d.). *MaximumPowerPointTracking—NIU - Virtual Renewable Energy Laboratory*. Northern Illinois University. Retrieved May 9, 2023, from https://renewablelab.niu.edu/experiments/MaximumPowerPointTracking

How Solar Power Finds New Uses In Rural Africa—The Solar Hammer Mill—CleanTechnica. (n.d.). Retrieved April 19, 2023, from https://cleantechnica.com/2019/08/12/how-solar-power-finds-new-uses-in-rural-africa-the-solar-hammer-mill/

IEA. (2022, June). *Key findings – Africa Energy Outlook 2022 – Analysis*. IEA. https://www.iea.org/reports/africa-energy-outlook-2022/key-findings

Lusaka, Zambia—Sunrise, sunset, dawn and dusk times for the whole year. (n.d.). Gaisma. Retrieved April 19, 2023, from https://www.gaisma.com/en/location/lusaka.html

Maximum power point tracking. (2023). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Maximum_power_point_tracking&oldid=1138906198

Mbumba, A. (2023). *The energy landscape in Zambia*.

Mulozi, D. L. (2008). *Rural Access: Options and Challenges for Connectivity and Energy in Zambia*.

Muneer, T. (1990). Solar radiation model for Europe. *Building Services Engineering Research and Technology*, *11*(4), 153–163. https://doi.org/10.1177/014362449001100405

Novergy. (2017, December 29). Solar Power Systems: String Inverter or Central Inverter? *Novergy Solar*. https://www.novergysolar.com/solar-string-inverter-vs-central-inverter/

Novia UAS website. (n.d.). Novia.Fi. Retrieved April 19, 2023, from https://www.novia.fi/en/about-us/

OMEGA Engineering inc. (n.d.). *What is a data logger? - Advantages of data logging*. Retrieved May 12, 2023, from https://www.omega.co.uk/prodinfo/dataloggers.html

pdglx. (2021, July 15). *Nominal Power in Photovoltaic – Solar Home Guide – Solar Home Guides*. https://www.solarhomeguides.com/nominal-power-in-photovoltaic.html

Positronic Solar. (2019, August 2). Panels, Shade and Diodes. *Positronic Solar*. https://www.positronicsolar.com.au/2019/08/02/panels-shade-and-diodes/

Power optimizer. (2022). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Power_optimizer&oldid=1125315118

Prakhar, J., Marpu, V., & Yerukola, P. (2022). *Power Optimizer Market Size, Share Analysis and Forecast—2031* (No. A16429; p. 305). Allied Market Research. https://www.alliedmarketresearch.com/power-optimizer-market-A16429

Rural Electrification Act 2003 – Policies. (2018). IEA. https://www.iea.org/policies/5910-rural-electrification-act-2003

Sendy, A. (2023, February 13). *Solar panel maintenance: Everything you need to know*. Solar Reviews. https://www.solarreviews.com/content/blog/solar-panel-maintenance-everything-you-need-to-know

Shandong Dejian Group Co., Ltd. (n.d.). *Solar Powered Milling Machine*. Made-in-China.Com. Retrieved May 9, 2023, from https://shandongdejian.en.made-in-china.com/product/vXsJIBhrCuUz/China-Solar-Powered-Milling-Machine.html

Short-Circuit Current | PVEducation. (n.d.). Retrieved May 3, 2023, from https://www.pveducation.org/pvcdrom/solar-cell-operation/short-circuit-current

Simulated historical climate & weather data for Lusaka. (n.d.). Meteoblue. Retrieved April 19, 2023, from https://www.meteoblue.com/en/weather/historyclimate/climatemodelled/lusaka_zambia_909137

Solar Edge Pros (Director). (2022, November 9). *Open Circuit Voltage of Solar Panels Explained*. https://www.youtube.com/watch?v=nTBXvt621SE

Solar Integration: Inverters and Grid Services Basics. (n.d.). Energy.Gov. Retrieved April 21, 2023, from https://www.energy.gov/eere/solar/solar-integration-inverters-and-grid-services-basics

Spring-2018-Floating-Solar-Project-Final-Report-Part-1-of-2.pdf. (n.d.). Retrieved April 19, 2023, from https://www.novia.fi/assets/Projectsites/EPS/projects/Spring-2018-Floating-Solar-Project-Final-Report-Part-1-of-2.pdf

Svarc, J. (2020, March 20). *Solar Panel Construction*. CLEAN ENERGY REVIEWS. https://www.cleanenergyreviews.info/blog/solar-panel-components-construction

Team Role Inventories. (2023). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Team_Role_Inventories&oldid=1148225775

The Nine Belbin Team Roles. (n.d.). Retrieved April 19, 2023, from https://www.belbin.com/about/belbin-team-roles

Use SolarEdge solar design software for commercial solar design. (n.d.). Retrieved April 18, 2023, from https://www.solaredge.com/aus/products/installer-tools/designer

Verelst, F. (2021). *Course: 21-22 Renewable energy*. AP University college.

Zambia. (2023). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Zambia&oldid=1150341188

Zambia | Tracking SDG 7. (n.d.). Retrieved April 19, 2023, from https://trackingsdg7.esmap.org/country/zambia

Zambia Electricity Access 1990-2023. (n.d.). Retrieved April 19, 2023, from https://www.macrotrends.net/countries/ZMB/zambia/electricity-access-statistics

Zambia Rainy Season: What to Expect. (n.d.). Natural World Safaris. Retrieved April 19, 2023, from https://www.naturalworldsafaris.com/blog/zambia-rainy-season-what-to-expect

ZambiaInvest. (n.d.). *Industry Archives*. ZambiaInvest. Retrieved April 18, 2023, from https://www.zambiainvest.com/industry/