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Design and Cost Analysis of an Off-grid Solar Grain Mill

Théogène Nshimyumukiza[1*], Christophe Bananeza[1],
Jean Marie Vianney Niyodusenga[1], Jean De Dieu Munyaneza[1]
and Etienne Iraguha[1]

[1]Department of Renewable Energy, RP/ IPRC Tumba, P.O. Box 6638 Rulindo, Rwanda.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Solar Energy in Rwanda is one of renewable energy sources that is being utilized nowadays in different remote regions of the country due to its considerable social-economic impact. The off-grid solar photovoltaic system turns solar irradiance into electricity to be used in remote areas without being connected to the national grid. Normally people living in those areas use diesel engines to perform their daily activities which require electricity and this has a crucial negative effect on the environment as they are contributing much to the environmental pollution. To address this problem and to reduce these effects caused by thermal engines, this project designs a solar system that will replace those thermal engines by not only reducing their environmental effects but also by allowing the households living in vicinity of system location to have easy access to the electricity. An off-grid solar grain mill provides the grain mill services to those people in remote areas far from the national grid. The system designed will use the solar home system components such as photovoltaic modules, charge controller, batteries and an inverter as generation components and grain mill machine. It has the capacity of 13.56kW whereby 7.5kW of them are used to run grain mill machines and the remaining are used by the local community for lighting purposes. Electrical design and simulation were done by using MATLAB SIMULINK for solar systems. The research method

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**Corresponding author: E-mail: theogenos05@gmail.com;*

includes weather condition, site survey, data collected from different organizations related to agriculture and energy sector. The system designed and simulated via software has shown good characteristics in terms of both performance and running grain mill machines. The overall system provided ways of getting services to people who don't have access to electricity especially whose daily life is agriculture based. The total cost of the project was estimated to be $29,690 with its annual income of $9,720 and then a payback period of 3.05years.

Keywords: Off grid; solar photovoltaic system; photovoltaic modules; charge controller; batteries; inverter; grain mill; rural electrification; renewable energy; hybrid system; carbon emission; MATLAB simulink.

1. INTRODUCTION

As our country moves faster towards sustainable development, the dependence of electricity for most everyday activities is a problem that leads to high production [1]. This dependence also demonstrates why electricity is regarded as one of the most significant sociological and economical in the agriculture sector in this period.

The agricultural sector is the oldest and most widespread industry in the world. In agriculture-based economies of sub-Saharan Africa particularly in Rwanda, agriculture is the main economic activity with 70% of the population engaged in this sector [2]. In Rwanda, the agriculture sector accounts for 33% of national GDP (Global Domestic Product). In general, Rwanda's GDP has been growing at the rate of 12.21% in 2019 [3]. Tea and coffee are the major exports while plantains, cassava, sweet potatoes, maize, rice, cassava flour, maize flour, poultry, and live animals with eastern Africa [2]. Transforming harvest in various areas under various economic, environmental, social, and political constraints is one of the major challenges.

The latest record on agriculture production for food in the world shows that many crops have been milled to produce flour for cooking. Traditional crops such as yam, sorghum, millet and teff have been milled for centuries either with a crude mortar and pestle fashioned from a tree stump and branch or by using flat stones or rubbing stones [4]. From the 18th century, the agriculture has advanced and the increase of plantations of different types such as maize, rice, beans, cassava, soya and other. Those harvests are for daily consumption by very big populated areas like military, schools and require to be transformed before being used. An example here is removing husks on the rice by hulling principle which is a process of applying friction to the grains to remove the outer part which is not consumable. This process is done traditionally by using two stones, knives or perforated plates. Rice has traditionally been hulled with mortar and pestle to remove the husk [4].

With the technology improvement where there is much wind associated with high speed, they developed the rotating system (wind mills) which is able to do the same task using wind energy to produce the desired product. This also failed due to the intermittency of wind and not also to be found in all locations on the earth. With the invention of the rotating machine in mid-nineteenth, the development of the high-speed rotating grain mill using electricity or fuel engine has become the best solution in industrial processing, especially small-scale industrial processing for problems of intermittent wind and the use of mortar and pestle which were used before.

In Rwanda there is a shortage of electrical energy, as in many developing countries, the demand of energy is superior to the production. Currently, the energy access is 52.8% corresponding to 224.6MW as total electrical generation and targeting to shift to 100% corresponding to 556MW by 2024 [1]. As the production of electrical energy is insufficient, to supply the power for all population and industries is more difficult. To overcome those problems, thermal engines using diesel, gasoline are used in rural areas for agricultural activities such as irrigation, small scale industrial processing of harvest to consumable products [5]. When burning fuel oil in an engine, it produces some amount of power but also a big quantity of smoke with high temperature is ejected into atmosphere as a result of combustion [6]. The heat and carbon emission sent into atmosphere cause climate changes, global warming, reduction of rain, sea level change, destruction of ozone and other negative impacts [7].

Ajan. A and K. Prem Kumar [8] the aim of their study was the development of a 5kW off grid solar PV system and to analyze the performance of that system under varying climatic change conditions. To achieve this objective of the study, the development of models of components on solar off grid systems has been developed in MATLAB SIMULINK and simulated. As a result of this research, SIMULINK model is used for performance analysis of the solar PV system under varying weather conditions. The power generation changes, energy efficiency of components and losses in the system have been quantified.

This paper has been selected due to the information that it provides related to the simulation of the result of solar off-grid system in MATLAB SIMULINK and as a useful tool to give sizing of components.

C. Aarthy Vigneshwari et al. [9] in their study whose aim is to propose the performance and economic analysis of on-grid and off-grid solar systems. To achieve their objective, a mathematical model of calculation of different economical parameters like payback period and profit were provided for having the ways of analysis. As a result of this research has shown that by calculation, both the systems tend to be economical over a period of time after the payback years. Even if maintenance cost and battery cost are very high for an off-grid solar system, the payback and profits are higher also as compared to on-grid solar systems. In their calculation, they end up by proving that the off-grid system is more economical and profitable as compared to the on-grid solar systems.

Brian Clarke and Alexandra Rottger [4] in their document whose objective is to provide information on various types of hullers and small mills available in Africa. It gives advice on how to select milling equipment, and how to install, operate and maintain small mills depending on their types.

Bhagyashree Mahale, Prof. Sapana Korde [10] in their research with the aim of identification of rice quality and evaluation of rice grains on the basis of grain size and shape using image processing techniques. To achieve their objective, they used a camera to capture a picture whose size is 640 X 380 pixels and that image is sent to the desktop computer so that it is manipulated(zoomed). NI labVIEW software is used to implement an image processing algorithm for analyzing the quality of the rice from that taken image. As a result of this research, there is classification of rice quality based on length, breadth and length-breadth. This paper has been interesting according to the ways of classifying grain based on their quality and this can be applied to grain to be processed on grain mill under design.

Shixiong Zhang et al. [11] in their study with the aim of designing a method for the controller of a flour mill with differential pair rollers driven by dual motors. The core concept in this research is to drive the fast roller and the slow roller of flour milling machine with respectively by two independent variable frequency motors in order to optionally adjust the rotating speeds of fast roller and slow roller and the rotating speed ratio of the roller-crushing flour mill within the allowable process range, thus realizing excellent flour milling effect. To achieve this, a model of the machine has been developed and simulated in MATLAB Simulink and the result has been present with the development of manufacturing process and control technology of modern flour milling and hulling. This document is used because they proposed a method of design of a flour mill.

This research is based on how to replace internal combustion engines, especially fuel engines used in agro-processing business by solar powered systems for reduction of emission in the atmosphere. It also shows how the electricity generation of the country can be increased through this process and therefore, there is increasing energy access and reduction of fuel oil used in transformation of different agricultural products toward development of the country and environment protection.

2. RESEARCH METHODOLOGY AND MATERIALS

In this research design and cost analysis of off-grid solar grain mill systems, there is a requirement of data related to agriculture sector, time of high production, weather conditions, cost of flour production, cost of electricity for development of systems with high performance.

This part is describing the method and materials used in research, research approach, the method which is used in data collection from different institution and people, the selection of sampling areas and community based on agriculture and energy sectors, the research process, data analysis based on electricity cost to flour production toward payback period, the ethical considerations and the research limitations of the project. All of these stages are achieved by use of Documentation from library, internet documentation, site visit survey, and use of software (MATLAB SIMULINK).

2.1 Research Method

This research was conducted using two different techniques which are qualitative and quantitative techniques. In order to enrich the objectives of this, a qualitative research was done. This includes interviews for asking people from rural areas the distance that they walk to get the flour for home consumption and to compare the flour produced using the fuels engines and the one produced using electricity for benefiting to the new project that can be implemented near them.

On quantitative techniques, there is recording of the weight that the customers bring to the current grain each and every day for knowing how much is the production needs to be processed per day or per week in a period of three months for knowing the capacity of the machine needed and money obtained for determining the payback period of the project.

In addition to this, there is recording the walking time in hours and distance in kilometer so that at the end of this project it will be possible to know the people who are suffering due to missing of nearest service provider. This was done on the existing two grain mills located in two different positions for having a good comparison of data to be used in design in a period of two months.

2.2 Data Collection Method and tools

2.2.1 Face to face Interviews

In this part of data collection, there is an interview to the owner of the grain mills related to the services that they provide, and to their customers to know the services that they receive.

For getting enough information to be used in this research, depth interviews are used. It has the aim of identifying rural people’s emotions, feelings, and opinions regarding the production of flour in the nearest place using solar powered systems rather than diesel engines.

The main advantage of these interviews is to involve the people who are benefiting from the use grain mill machine since they are the main customers. This interview was offered in order to get correct information related to the crops production according to each season, availability of some type plant like cassava which is available one time in the year and others which are available for every season.

All of this information from the customer services for two different sites are summarized in Fig. 1 which helps in data analysis and estimation of payback period of the designed project.

As a result of this interview the crop production graph was produced

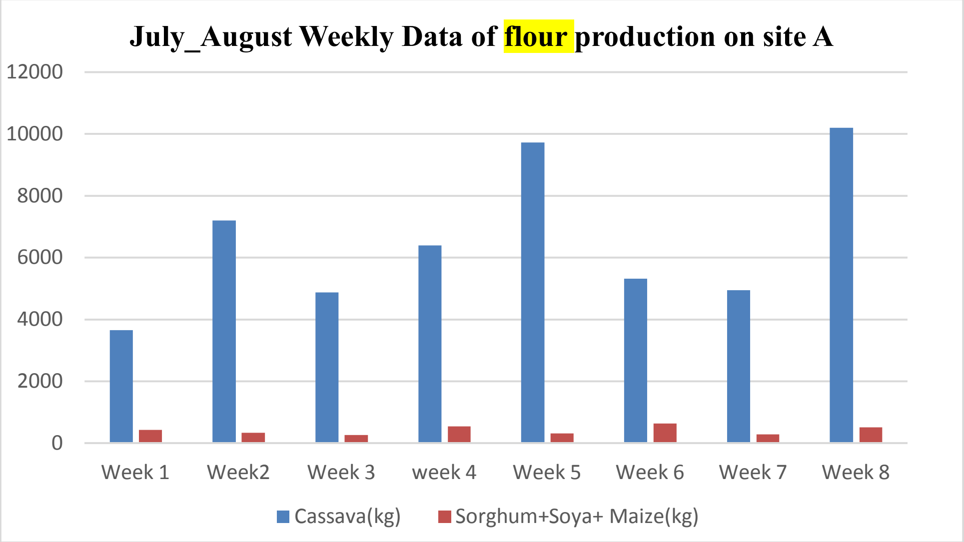

Fig. 1. Flour Production on site A

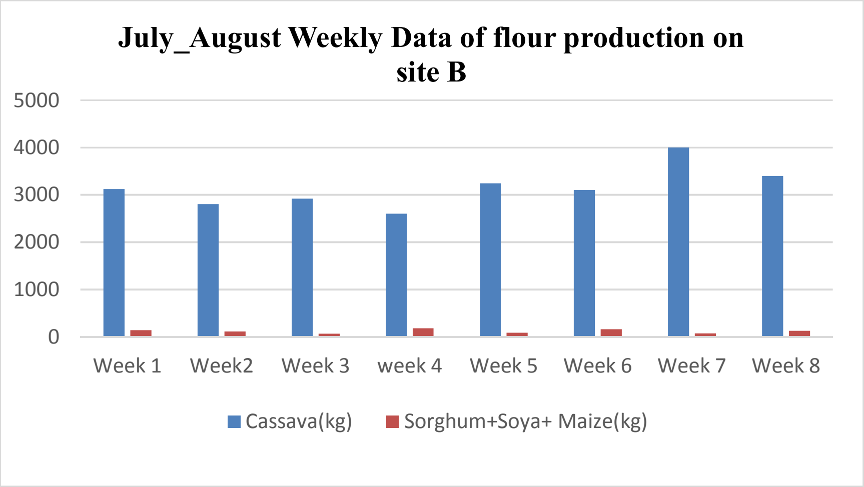

Fig. 2. Flour production on site B

From the above graphs, the average flour production is 850kg per day on Site A

From Fig. 2, the average flour production on this site is 420kg per day on Site B.

Combining the two sites the average production per day becomes 650kg per day but this value can go up or down for some time.

2.2.2 Data collection from organizations

Apart from the interviews, there is also data collection related to weather conditions and climatic changes which will be used in the design of the sustainable system.

Those data include precipitation, temperature, wind speed and direction, irradiance, peak sun hours in each district. These are more useful in the design of the solar system because depending on the region the same machine will not have the same performance. This is obtained from the Rwanda Meteorology agency.

In addition to this, there is also to know the crop production in Rwanda and specification of each depending on the region. An example here is that in Eastern province of Rwanda, the production of maize is more advanced that other regions. So, the design of the machine which will be used in that region has to be done carefully and with precision and with a powerful storage system due to many working hours per day. This is obtained from the Ministry of Agriculture and Animal Resources and from surveys to the existing gain mills.

Lastly, there is also the need to know the electricity cost and the focus areas where there is no electricity. This is based on the fact that the energy access in Rwanda is 52% and the remaining part of about 48% is in black out. To know this part without electricity requires data from Energy Utility Corporation limited (EUCL)

2.2.3 Areas of focus

As of September 2020, the cumulative connectivity rate is 56.7% of Rwandan households in which 41.3% are connected to the national grid and 15.4% accessing off-grid systems (mainly solar home system) [1].

Most of people with challenge in energy access are located in villages especially with agriculture based and to have electricity requires high cost due to long transmission lines and in their low income.

The current access targets stipulate a 100% household's access to electricity by the year 2024 while productive users will be all connected before the end of the year 2022. To achieve this target, REG intends to increase the number of new connections by 500,000 every year, including 200,000 on-grids and 300,000 off-grids [1].

To get well the areas of focus there is requirement of knowing which region is having electricity and which region is not having electricity.

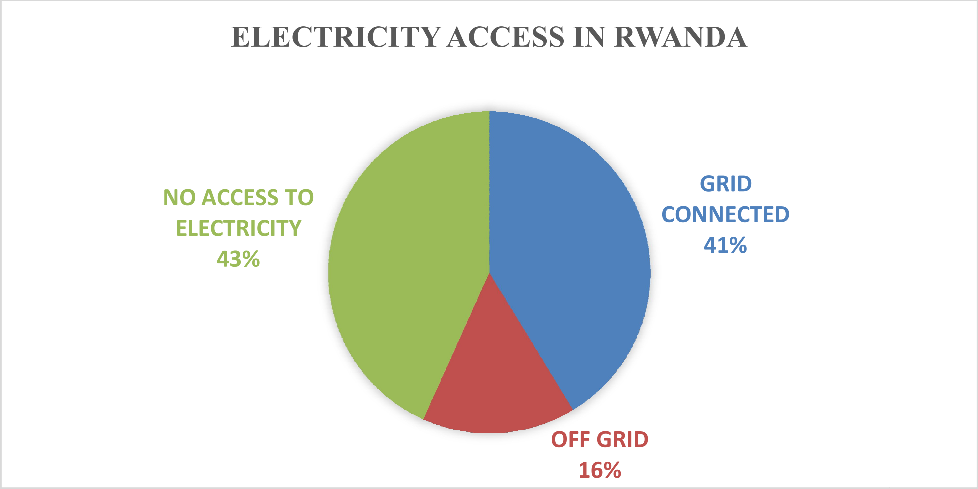

Fig. 3. Electricity access in Rwanda

2.2.4 Cost of electricity in Rwanda

The main aim of this part of cost of electricity is to know how much it is sold so that the local community is able to pay the same amount and to allow use the calculation of payback period from income generated in the project under the study.

The electricity cost in Rwanda is based on how much the consumption per year. This consumption allows having categories that are used in payment of electricity. The average cost per kWh is calculated.

2.2.5 Instruments or equipment (tools)

To achieve the main objective of the project, there is the requirement of knowledge of the capacity of the machine under design and this correspond to the weight of grain in kg coming for servicing. The weight is recorded to two different positions by use of spring balance.

On other hand, there is the need of the solar radiation capacity to know how much can be generated because the output of solar system is based on irradiance input. This is measured by Lux meter in W/m^2.

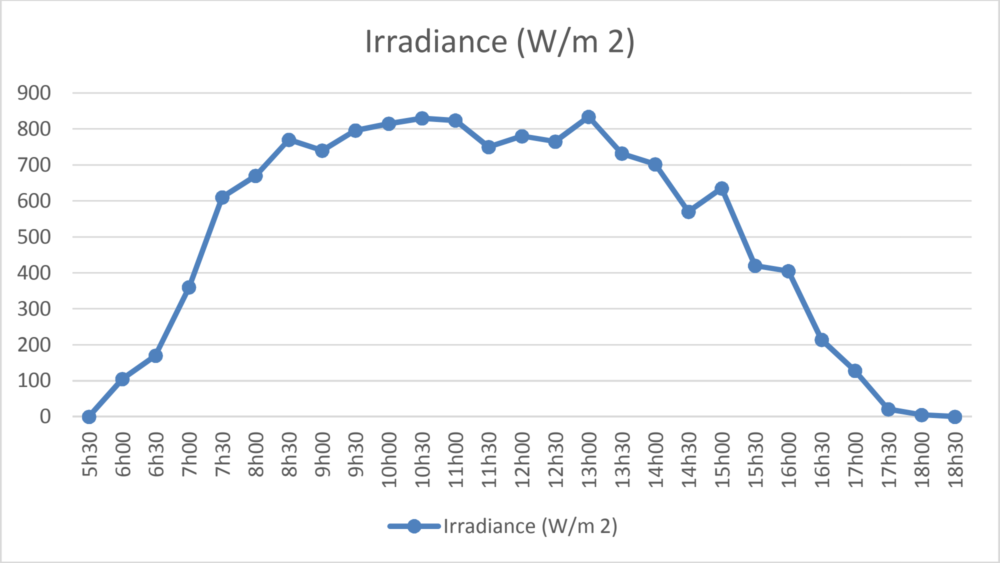

Fig. 4. Average solar irradiance

All of this information has been taken in one week from Monday to Sunday after each 30min during the day and compiled by calculating the average. It shows that the irradiance is quite good between 5h30 and 18h30 for eight months including in dry and rain season.

2.2.6 Energy demand for surrounding community

Sample of the communities were taken also on two different site names Site A and B of remote areas far from national grid near grain mills using diesel engines. On each site 15 people were interviewed on the electricity need, Ubudehe categories.

Among all the people interviewed, all categories are available in the country are also available on this site.

On site B also all categories are available which can allow to know the capacity of the them to be able to pay whenever the plant is constructed.

In Addition to their categories, based on the number of people located in sampled remote areas where there is no electricity the basic need of electricity is for home lighting for houses. The common load that they are willing to have lightings for their houses.

According to an interview with the leaders, site A is growing at a rate of 2 households per year while site B of 3 households per year.

2.2.7 Simulation through software

To obtain the expected results within the framework of this work, the following software are adapted to execute the project.

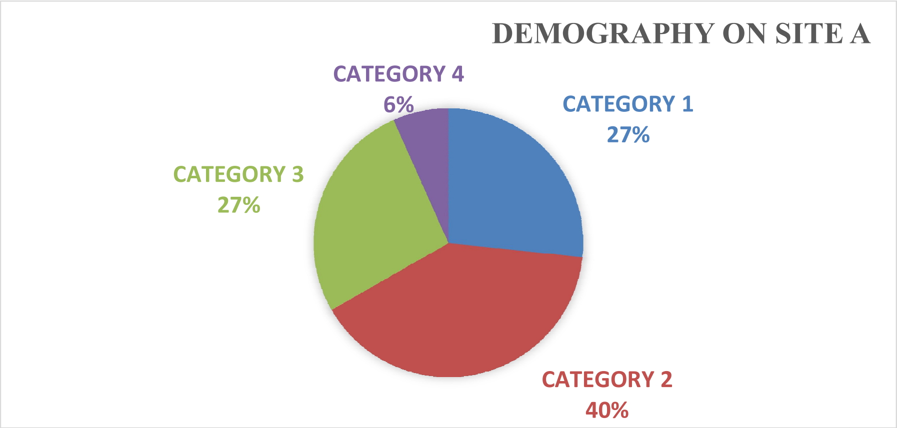

Fig. 5. Ubudehe Category on site A

Table 1. Local community assessment result

	SITE A	
Family Number	**Number of rooms in needed of light per family**	**Number of outdoor lamps per family**
5	5	2
6	7	2
5	3	2
4	4	2
Total number of families	20 families	
	SITE B	
Family Number	**Number of rooms in needed of light per family**	**Number of outdoor lamps per family**
7	5	2
4	7	2
2	3	2
3	4	2
Total number of families	15 families	

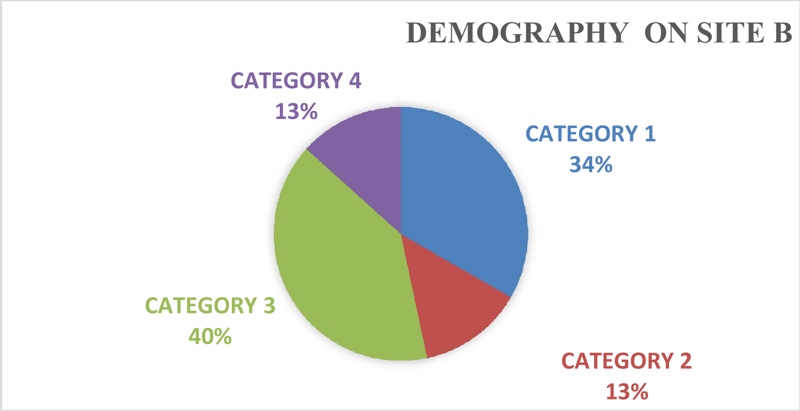

Fig. 6. Ubudehe Category on Site B

MATLAB SIMULINK used to simulate the electrical side of the system under design of the project. This include all part of the solar system from generation to load where all required parameters are inserted to produce the required output. In addition to this it is also used in this project in cost analysis of the system toward payback period. The available version used in this project is 2020 and contain almost all feature required in design of an off-grid grain mill machine

3. DESIGN OF AN OFF-GRID SOLAR GRAIN MILL AND SURROUNDING COMMUNITY

Design of an off-grid solar system is normally based on the load which is going to be used on that system and the time it will be used [12]. The loads that are commonly used in those areas fall from national grid generally are lighting bulbs, televisions, few irons and some grain mills which require huge electricity.

This part is based on design of an off-grid system which is providing electricity to be used by a grain mills for small scare industrial processing business for providing services to people located in remote areas fall from national grid.

It is describing all solar off-grid components and the loads which are grain mill machine and surrounding community.

3.1 Induction Motor Selection

The analyses of the harvest available on the field has given 650kg and available on the average time of 5hour per day. This means that the required machine must be able to process 150kg per hour or 2.5kg per min. This depends on the type of the grain or product to be transformed and on the type of screening used in the machine.

We know that the torque developed by an induction motor is given by:

$$T_{sh} = 9.555 \times \frac{P_{out}}{N} \tag{1}$$

Where the T_{sh} is the shaft torque in Nm, P_{out} is the power developed by the motor in kW and N is speed of the induction motor in revolution per minute (rpm).

Resistive Torque which is the load driven is also depending on the mass that the load has and on the displacement.

$$T_{resistive} = F \times r \tag{2}$$

$$F = m \times g \tag{3}$$

Where F is the Force, r is the radius of hammer, m is mass of driven load.

Here the mass of resistive (load) is the one of grain falling inside and the mass of hammer.

$$m = m_{grain} + m_{hammers} \tag{4}$$

Mass of grain entering in the machine to be 2.5kg and mass of hammer to be 2.5kg with radius 200mm so that the total mass of load is 5kg. The value of resistive torque obtained is $T_{resistive} = 10Nm$.

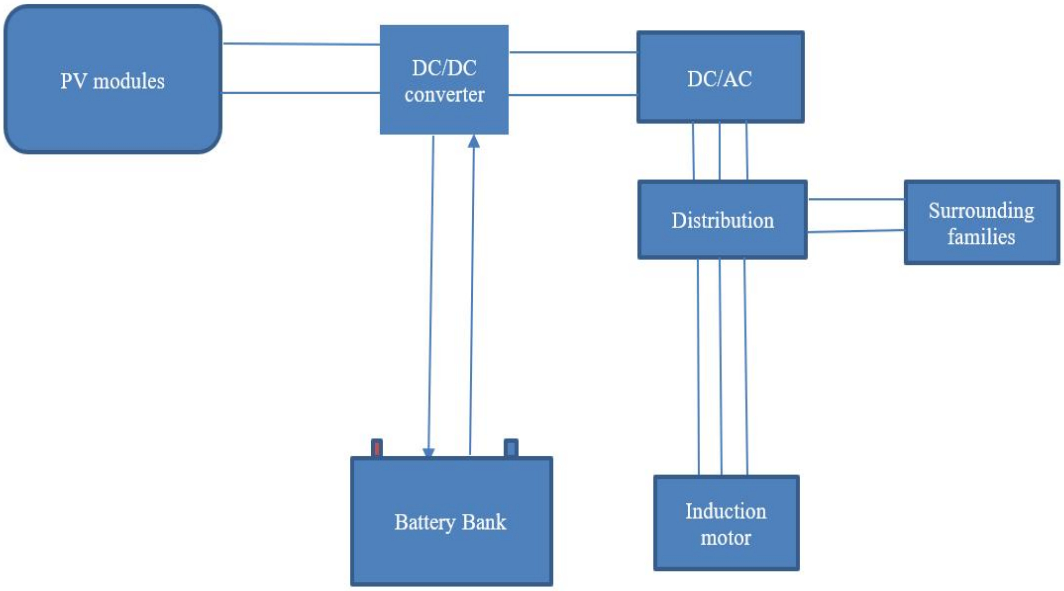

Fig. 7. System block diagram

To keep the induction motor still running, the following relation must be taken into consideration $T_{resistive} < T_{sh}$.

Let also take into consideration that the $T_{resistive} = T_{sh}$ so that it is possible to calculate the output power required from eq.1.

$$P_{out} = \frac{T_{resistive} \times N}{9.555} \tag{5}$$

The mill under design is directly connected with the induction motor without any change on the speed. The grain mill has the same speed to the induction motor. By considering the speed N to be 3000rpm, the output power becomes 3.139kW.

When the motor of this rating is connected to the system, it will not run due to the resistive torque equal to the motor torque. So, to have the running system the following relation have to be obeyed $T_{resistive} < T_{sh}$. The motor capacity must be greater to that value obtained by load torque. Predicting for future production having the machine of high reliability and strength the selected, the selected motor to be considered in this design to be of 7.5kW induction motor.

An AC induction motor of 7.5kW which is working up to 5hours per day driving a grain mill, this time was chosen base on the production of the machine which is 150kg per hour and on average crops coming to the grain mill for servicing per day which is 650kg.

The best type of induction motor on grain mill machine is a squirrel cage induction motor having specific characteristics based on the application.

This motor is able to work as a fan having 2860rpm, so it is able to create the pressure that can allow the flour produced to pass through screening system. If the speed is too small the mechanism of separation is not possible.

3.2 Surrounding Community Load Assessment

Based on the number of people located in sampled remote area where there is no electricity the basic need of electricity is for home lighting for houses. The biggest load to be considered in this design is lighting light bulbs.

Table 2. Motor characteristics

Power	Voltage(V)	Frequency (Hz)	Speed (RPM)	Current(A)	Connection
10hP/7.5kW	400	50	2860	15.7/9.1	Delta/star

Table 3. Local community assessment result

	SITE A		
Family Number	**Number of rooms in needed of light per family**	**Number of outdoor lamps per family**	**Total Number of lamps**
5	5	2	35
6	7	2	54
5	3	2	25
4	4	2	6
Total number of families =20	Total number of lamps		120
	SITE B		
Family Number	**Number of rooms in needed of light per family**	**Number of outdoor lamps per family**	**Total Number of lamps**
7	5	2	49
4	7	2	36
2	3	2	10
3	4	2	18
Total number of families =15	Total number of lamps		113

To have a system which can help in energy access on some percentage and to limit the cost of the project, the site A was considered in design. Therefore, Total number of lamps on the plant becomes 120lamps.

Taking a 220V AC of 20W lamp per each used 6hours per day as many uses lighting before sleeping

$$E_{\text{demand families}} = 120 * 20W * 6h = 14400Wh$$

3.1 PV sizing

The PV sizing start with the calculation of energy demand to know how much is required in terms of energy.

$$TEED(\text{Total electrical energy demand}) = E_{\text{demand mill}} + E_{\text{demand families}} \quad (6)$$

$$TEED = (7.5kW \times 5hours) + 14.4kWh = 51.9kWh \quad (7)$$

$$\text{Total energy required on PV per day} = \frac{\text{Total energy demand}}{\text{Global efficiency of the system}} \quad (8)$$

$$\text{Global efficiency of the system} = \eta_{battery} \times \eta_{inverter} \times \eta_{regulator} \times \eta_{cable} \quad (9)$$

Assuming global efficiency of the system to be 0.85,

$$\text{Total energy required on PVs per day} = \frac{51.9kWh}{0.85} = 61.058kWh \quad (10)$$

Based on this agreement found between the approaches used in estimating the solar energy resources over Rwanda, the average minimum value is 4.3 kWh/m^2/day and per day while the maximum is 5.2kWh/m^2/day[13],

$$\text{Total required power} = \frac{\text{Total energy required on PVs per day}}{\text{Peak Sun hours or panel generation factor}} = \frac{61.058kWh}{4.5h} = 13.56kW \quad (11)$$

On the market there is different size of the PV module and by choosing any one of them the number to be used in the design also will change. Consider the following characteristics of PV datasheet to be used while calculating:

Peak power (Pmax) =325W, Open circuit voltage=46.38V, Maximum power voltage (Vmp) =37.39V, Short circuit current (Isc) =9.17A, Maximum power current (Imp) = 8.69A and Maximum system voltage 1000V.

By using that information from the name plate of the PV, we can calculate the number of panels that are required in production of 13.568kW.

$$\text{Total number of panels}=\frac{\text{Total power to be generated}}{\text{Power generated by single panel}}$$

$$=\frac{13.568kW}{325W}=42\,panels \qquad (12)$$

For arrangement purpose and good appearance of the plant let take 40PVs instead of 42PVs.

Another important parameter to be considered in the design is the maximum system voltage. On the data sheet that we are using from above, the maximum system voltage is 1000VDC which means that we are not allowed to connect all those PVs in series so that we exceed this maximum system voltage.

$$\text{Number of penel in series}=\frac{\text{Maximum system voltage}}{\text{Open circuit voltage for single panel}}$$

$$=\frac{1000V}{46.38V}=21PVs \qquad (13)$$

To simplify the design and purpose easier in cleaning and other maintenance activities, we can connect 8PVs in series which will bring operating voltage of 371.04VDC at open circuit instead of 1000VDC and of short circuit current of 9.17A since when putting PVs in series the voltage will be added up but current remain the same.

$$\text{Operating voltage at open circuit}=8\times 46.38\text{Vdc} \qquad (14)$$

This voltage is for operating voltage at open circuit is obtained at maximum power and corresponding to the maximum voltage (Vmpp) is 299.12V.

$$\text{Operating system voltage}=\text{Maximum voltage}(V_{m_{pp}})\times\text{Number of PVs in series}$$

$$=37.39V\times 8=299.12V \qquad (15)$$

The short-circuit current is $I_{sc}=9.17A$

These 8PVs form a string whose power can be calculated as follows:

$$\text{Power per string}=\text{Power of single panel}\times\text{Number of panels per string}$$

$$325W\times 8=2600W=2.6kW \qquad (16)$$

$$\text{Total number of string}=\frac{\text{Total power}}{\text{Power per string}}$$

$$=\frac{13.568kW}{2.6kW}=5strings \qquad (17)$$

These 5 strings are going to be in parallel therefore their output system voltage will remain constant of 371VDC while their output short circuit current will be increase to *45.85*A.

$$I_{sc}=\text{Short-circuit current of the string}\times\text{Total number of strings}$$

$$=9.17A\times 5=45.85A \qquad (18)$$

3.2.1 General PV layout and connection

The below block diagram shows the arrangement of all 36solar panels grouped into 5strings in parallel as calculated and each string having 8solar panels connected in series.

This arrangement facilitates in reduction of space occupied by these PVs, easy of cleaning and maintenance due to free space between two successive strings. The cost of the conductor is reduced also since positive and negative terminal are connected directly without any extra cable and positive because they are on the same side of a string.

These panels would be mounted on racks, Solar modules shall be installed at an angle between 10^0 and 20^0 from the horizontal plane depending on location in the country to maximize the system for annual energy production [14]

3.3 Power Conditioning Unit Sizing

This is a set of inverters, charge controller, Boost converter with MPPT system and control system.

Charge controller should be able to support short circuit current (I_{SC}) of the module and maximum battery current to load current (IL max). Where the load current can be calculated by using following equation,

$$I_{L_{\max}}=\frac{P_{total}}{V_{battery}} \qquad (19)$$

The selection of the solar charge controller will depend on the output parameter especially current, voltage and power that are coming from the string designed in the project.

As calculated, the charger controller input will be having Voltage of 299.12V and Current of 43.45A and the output related to the input of the battery.

$$I_{L_{\max}}=\frac{13.568kW}{96V}=141A \qquad (20)$$

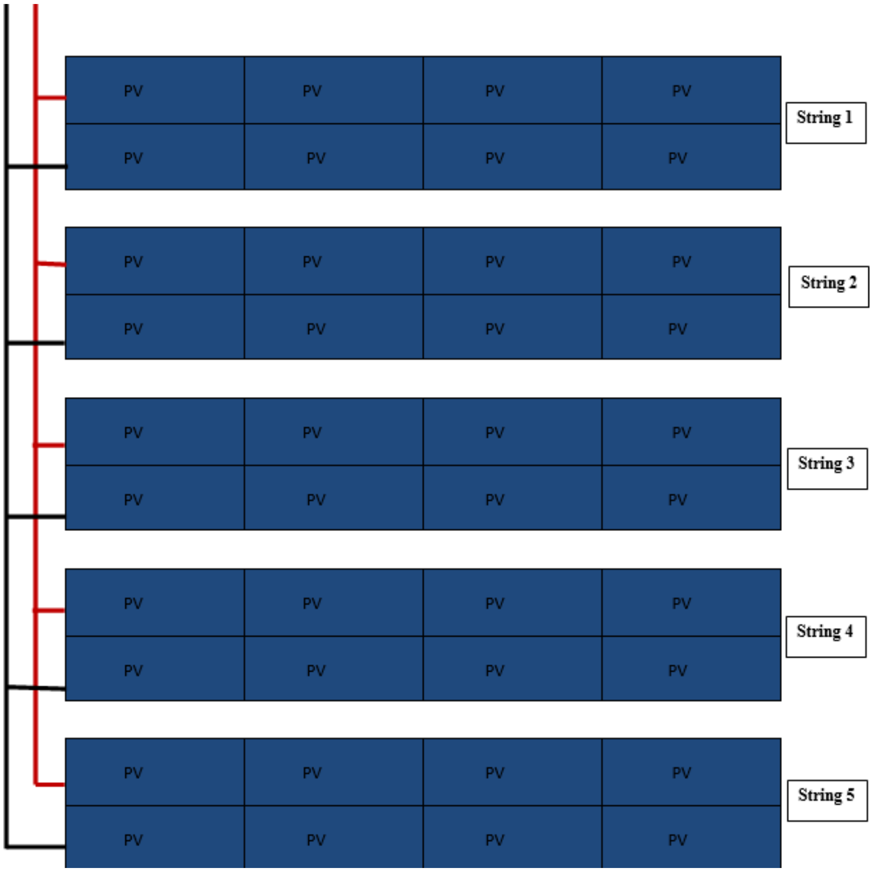

Fig. 8. PVs layout

According to standard practice, sizing of solar charge controller is to take short circuit current (Isc) of the PV array multiplied by 1.3 [15]

$$\text{Solar charge controller current rating} \\ = \text{Total short-circuit current of PV array} \times 1.3 \quad (21)$$

In this case, the short circuit current (I_{SC}) is: $I_{sc} = 9.17A \times 5 = 45.85A$

Then from the eq.21

$$\text{Solar charge controller current rating} \\ = 36.68A \times 1.3 = 47.684A \quad (22)$$

The charge controller to be used in this system must allow the flow of current of 47.684A.

On the other hand, an inverter capacity is determined by the peak load demand connected to it. Peak load demand is calculated using the relationship between the connected load and the diversity factor (DF) of the load at where the diversity factor is the ratio between maximum demand and the total connected load [16].

$$P_{inv} = \sum_{i}^{n} \frac{P_i \times n_i}{DF} \quad (23)$$

Where Pi is the power consumption of any device of type i connected to the PV system and ni number of devices of type i.

$$\text{Total power} = 7.5\text{kW} + (120 * 20) = 9.9\text{kW} \quad (24)$$

The inverter should be 25-30% bigger than total Power of appliances so that it is able to supply them and support the starting current. From this statement 30% of 9.9kW is 2.97kW and then the power capacity of this inverter is 12.87kW.

Most of the time the capacity of inverter is expressed in kVA and in this research the power factor $\cos\varphi$ was considered to be 0.95. The apparent power can be calculated as shown in eq.25.

$$S = \frac{P}{\cos\varphi} \tag{25}$$

By applying the above formulae, the capacity of inverter to be used in this project will be of 13.54kVA which can be approximated to 14kVA

The selected inverter is a three phase, sinusoidal waveform of 14kVA based on the required power of the plant and the on the working conductions to support the load.

3.4 Battery Sizing

Due to the difference between the variation of load power and solar power generation at any given time, the battery storage system is required to supply or absorb this variation. In system design, the battery along with the inverter system, placed between the rooftop PV panels and the load [17].

To determine the size and number of batteries it is more important to know the Energy require per day (E_{day}), Number of day(n_d) that the battery can save power also called days of autonomy, Rating of the battery to be used expressed in Ah (I_h), Nominal voltage of the battery (V_{bat}) and depth of discharge (DoD) of the battery system.

In this design the, lead-acid type (Pb) is selected due to its characteristic performance, availability on market and its low cost.

$$\text{The number of batteries (Nbat)} = \frac{E_{day} \times n_d}{V_{bat} \times I_h \times DoD} \tag{26}$$

By using lead-acid type (Pb) of the following characteristics:

Battery capacity of 200Ah, nominal voltage of 24V, depth of discharge (DOD) of 0.6 with day of autonomy of the system to be 2days

Also, this design is always based on the load which is available on this system. Now in our case the load is a grain mill machine of 10KW and the service that it gives is 5hours during for 7days.

Therefore, the Energy consumed per day will be given as follows:

$$\text{Energy per day} = \text{power consumption of load} \times \text{time it works per day} \tag{27}$$

From the eq.27 the energy per day is $E_{day} = 51.9kWh$. From the eq.26, the number of battery is calculated as:

$$N_{bat} = \frac{51.9kWh \times 2}{24V \times 200Ah \times 0.6} = 36batteries \tag{28}$$

The output from PV string voltage is 373.9VDC as calculated in previous and forming the battery bank of 432V for the system as the input to the batteries, therefore

$$\text{N}_{bat}\ \text{in series} = \frac{432V}{24V\ \text{per each battery}} = 18batteries \tag{29}$$

This mean that the 4batteries will be in series on one side of the battery bank and therefore the system will have 2lignes in parallel each having 18batteries

3.4.1 Battery layout

Connection of batteries 18bateries in series to form 432V on the battery bank is shown in the above figure.

The Fig. 8 presented herewith shows the set of 32batteries connected together to form the battery bank as storage system. The 4 batteries are connected together in series for limiting voltage and current.

$$V_{\text{battery bank}} = V_{bat} \times N_{bat} \Rightarrow V_{\text{battery bank}} = 24V \times 18 = 432V \tag{30}$$

By connecting them in series the voltage increases and the current remain constant on one horizontal of battery bank. So, connecting them in parallel will change the current while the voltage remains constant.

$$I_{\text{battery bank}} = I_{bat} \times N_{bat} \tag{31}$$

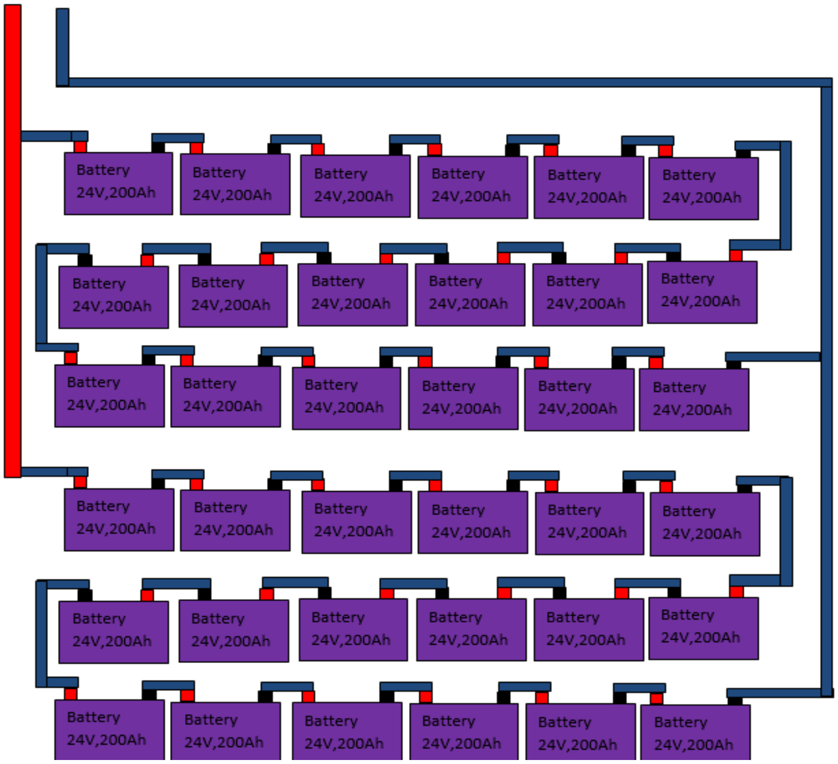

Fig. 9. Battery bank

3.5 Cable Sizing

3.5.1 Wire between PVs and Power conditioning unit

The wire joining solar module and Power conditioning unit must be as short as possible and resistant to solar radiation and water as well as ultra violet (UV) rays in sunlight. The inner diameter of the conductor depends on voltage drop between PVs and Power conditioning unit. The thickness of the conductor indicates how much energy in terms of heat can be dropped between the solar module and Power conditioning units.

The size of the wire required is calculated by using the Standard Wire Gauge (SWG) formula as following [18].

$$S = \frac{0.3 \times L \times I_{PV}}{\Delta V} \qquad (32)$$

S is cross section area (mm^2), L(m) length of the conductor between PVs and charge controller, I_{PV} is the current flowing from PV to charge controller (Ampere), ΔV indicates the voltage drop or voltage loss across the wire and its maximum allowed value in percentage is 5%.

$$S = \frac{\pi d^2}{4} \quad \text{and} \quad d = \sqrt{\frac{4S}{\pi}}$$

With,
S = Cross sectional area of wire (mm2)
d= Diameter of wire (mm)
Considering L = 5m, IM= 75A and ∆V= 5% and based on the above formula the cross-section area of the conductor is 11.3mm^2 or 3.8mm of diameter.

3.5.2 Wire between Power conditioning unit and battery

The size of conductor between charge controller and battery is also calculated by using previous equations but considering the value of ∆V to be taken as 1%. No need to use UV protected wire because it is located inside the house and also supporting the large current when discharging by supplying the load. During the charging, the current flowing through this wire is the same as current from PVs (I_{PV}) and during discharging process the current in this wire is equal to load current connected to it. The value of current taken for calculating the cross-sectional area should be the higher value of both current which is exactly load current so that it will be able to supply the load when it is discharging.

$$S = \frac{0.3 \times L \times I_{L_{\max}}}{\Delta V} \tag{33}$$

Load current $I_{L\max}$ in our case is 15A and ΔV is 1% and with length L of 1m then S=0.75mm^{2}and d=0.98mm.

3.5.3 Wire Between Power conditioning unit and load

In this part of the system, ΔV is less than 5% and by using eq.33 of cross section area for calculating the size of the wire between inverter and loads.

In our case $I_{L\max}$ is 15A and ΔV is 2% and with length L of 4m then S=4mm^{2}and d=2.2mm

4. SIMULATION RESULTS OF COMPONENTS IN MATLAB SIMULINK AND DISCUSSION

After calculating all the values of current, power and voltage of each component using mathematical formulae, these values become the input to each component of the solar system.

The following block diagram shows the electrical side developed in MATLAB SIMULINK and then the result on each component represented aside. Due to the length of the block diagram, the elements of each component have been compressed together to create a subsystem.

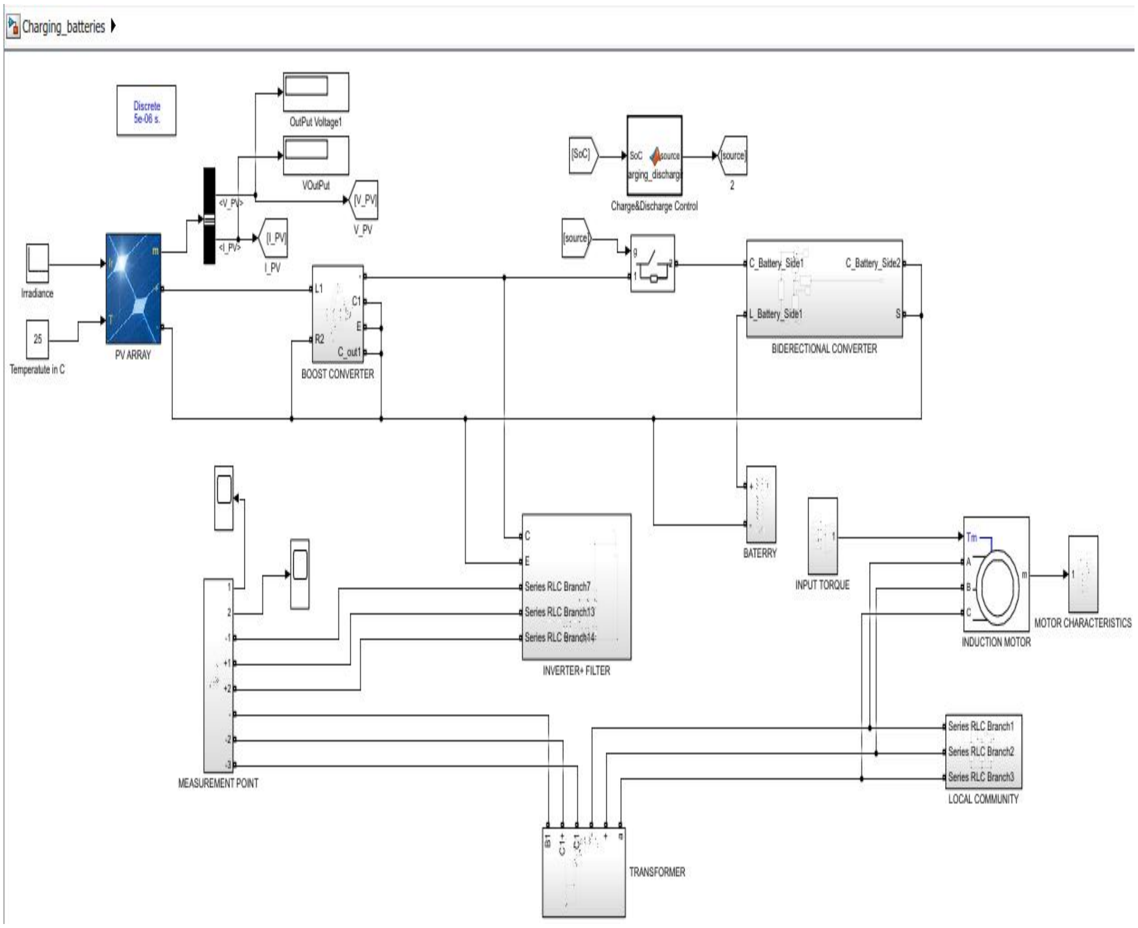

Fig. 10. Simulation of components

By simulating, the information related to each side were extracted, presented and analyzed.

4.1 PV Output

After inputting the number of modules in series calculated above and the number of strings in parallel to the module block in MATLAB SIMULINK then plot the IV curve of the system designed under different irradiance values.

By arranging 8PVs of 335W each in series to form a string and combining 4strings in parallel and plotting the IV curve of the output of the system, the output will vary depending on the input irradiance.

As the input irradiance decreases, the output current also decreases and this affects the output power of the all system. This has the meaning by comparing the output power of solar PV at different times during the day. Before noon the output power on PVs is higher than the afternoon power generation due to high intensity of sunshine.

Here the voltage is presented on x axis while current is on Y axis and the corresponding value of power p is calculated as $P = V \times I$

This shows that the output maximum output current I_{max}= 40.35A and maximum voltage V_{max}= 332V

The maximum power output P_{max}= 13400W this at corresponding to 1000W/m^2 which is not possible in real life.

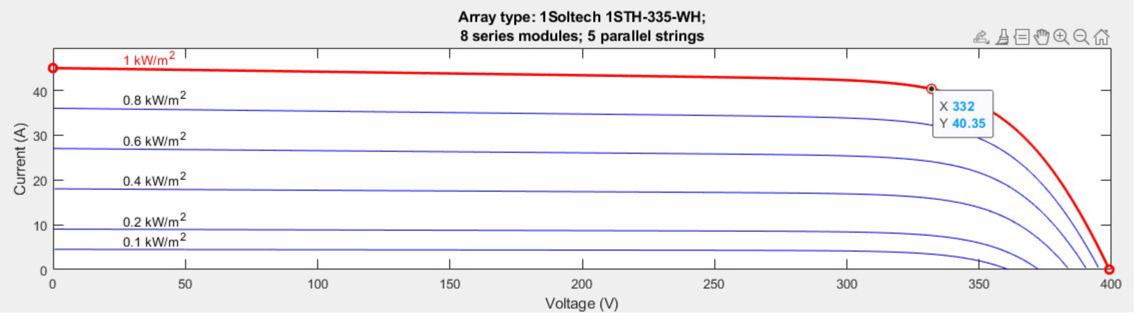

Fig. 11. IV Curve with different irradiances

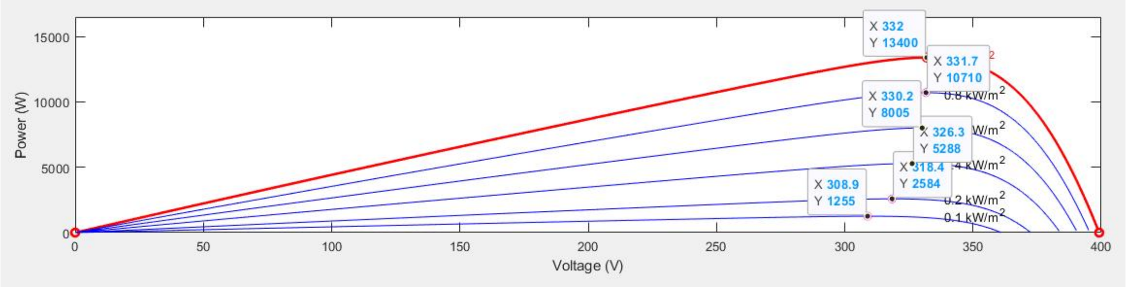

Fig. 12. Power output with different irradiances

Table 4. Result from PV

Irradiance (kW/m^2)	Current(A)	Voltage(V)	Power(kW)
1	40.35	332	13.400
0.8	32.32	331.17	10.71
0.6	24.24	330.2	8.005
0.4	16.2	326.3	5.288
0.2	8.12	318.4	2.584
0.1	4.06	308.9	1.255

The output power of the designed system reduces with a reduction of the irradiance.

By running the system in MALTAB SIMULINK the output voltage of output from the PV is ranging between 0 and 330V depending on the value of the input irradiance.

Since the system is working by the use of perturb and observe to attract the maximum power point it just records the point of maximum output power.

The output is changing depending on the input irradiance. When the irradiance goes to zero, the output voltage also goes to zero and there is no power generated in that case on PVs.

On other hand, the output current of the PV is in the range between 0 and 35A depending on the input irradiance.

4.2 Boost Output

The following result output was produced in MATLAB SIMULINK by simulating the converter.

By increasing voltage from low value to high value the output voltage is able to charge the battery and increase in the state of charge.

The output after boosting is very large as compared to the input of the PVs.

The voltage has been increased here in the range of 0 to 330V of PV level and became in the range of 0 450V depending on the input irradiance after boosting and this has the effect on the process of charging of the battery.

An increase in voltage causes the decrease in current to keep the output power constant. Here the output current from PV was between 0 and 35A which has decreased to the range between 0 and 25A depending on the irradiance input.

4.3 Battery Side

On other the hand there is a need of storing the electrical energy from the boost converter and it is not done randomly. The need for internal arrangement of them and production of the same voltage as the one produced by boost and for the purpose of increasing state of charge.

By running the program, the state of charge which was initial to 45% starts to increase as follows increase slowly until it reaches the maximum state of charge.

As the state of charge increases the energy is being stored in battery and it takes some time to increase from the initial state of charge to the final state of charge which is at 100%.

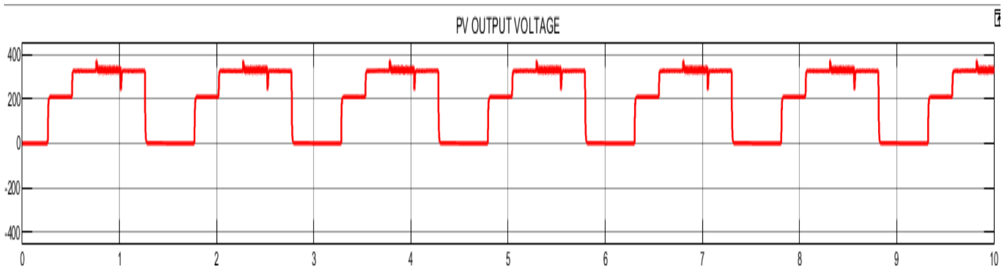

Fig. 13. Resulting output on PVs

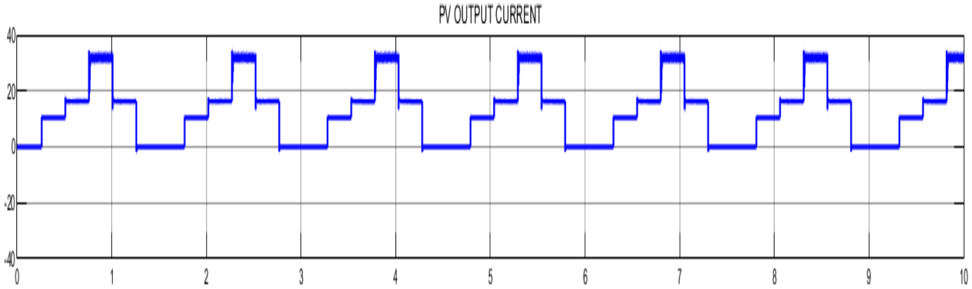

Fig. 14. PV Output Current

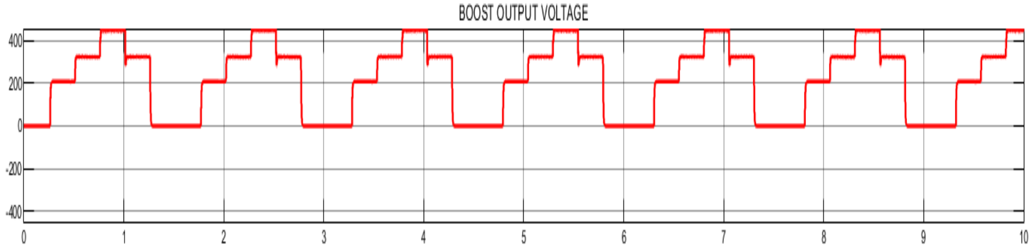

Fig. 15. Voltage Output after boosting

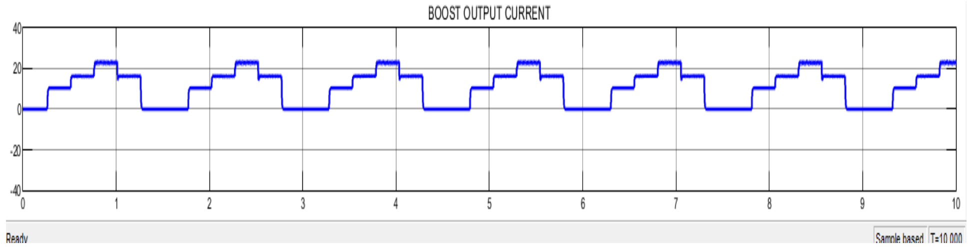

Fig. 16. Output Current after boosting

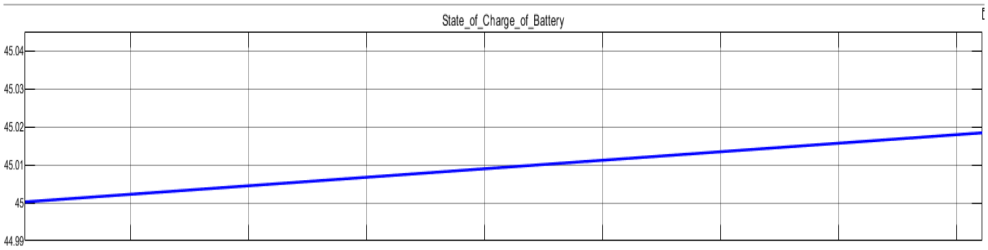

Fig. 17. State of charge

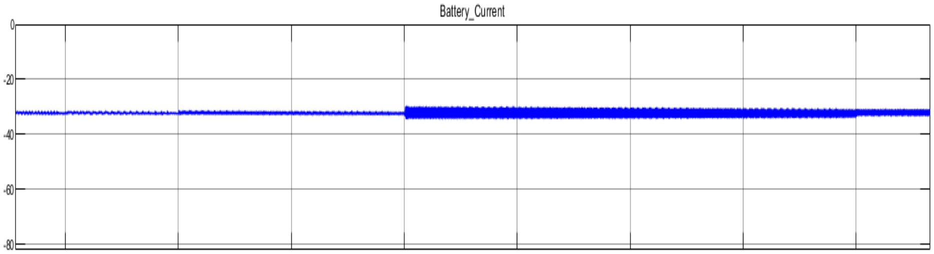

Fig. 18. Battery current

When simulating, the battery voltage and current will change by given value depending on whether charging or discharging. It is charging when the input irradiance is somehow high and discharging when it is low while the load is connected to it.

Like the graph in Fig. 17 shows the discharging process of the battery at night for supply or in ground period when there is no sunshine. It has been obtained by setting the input irradiance to 0 and running the system. In this case, the output power from PVs becomes 0 while the load demand is available. The battery bank reacts by supplying the stored energy to the surrounding families and grain mill machine.

Whenever the battery is under charging its related voltage will be increased by some amount so that the charges will be stored in the battery. The battery is on around 110V when it is charging.

4.4 Inverter Side

Inverter output before connecting transformer.

The inverter output voltage is not able to run the machine due to its lower value as compared to the motor rating. The motor rating is of 400V as the voltage while the output voltage of the inverter is in between -40V and 40V.

This level of voltage needs to be stepped up to have the standard rating that is possible to be used by the induction motor and the local community. The only way to change the high value is to step it by using a step-up transformer which increases the level up to 400V.

The presented voltage is the line neutral voltage and it of 230V and by measuring the voltage between the two phases, the value obtained is of 400V as the one of national grid

4.5 Induction Motor Parameter

The induction motor used in this project is a three-phase motor of 7.5kW,400V, 2860rpm other remaining parameters like current and torque are being calculated and inserted to the block in MATLAB SIMULINK.

$$N_s = \frac{120f}{p} \tag{34}$$

Where f is frequency and it is 50Hz and p is number of poles

N_s =3000rpm this is never attained on an induction motor practically. So, it varies between that value and 2700rpm depending on the load(torque) connected to it.

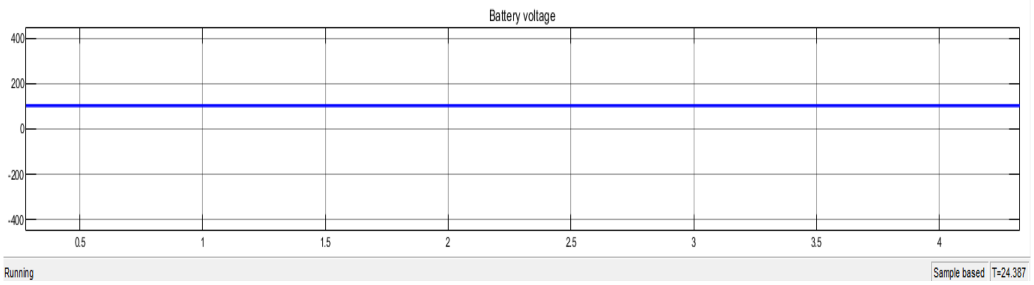

Fig. 19. Battery voltage

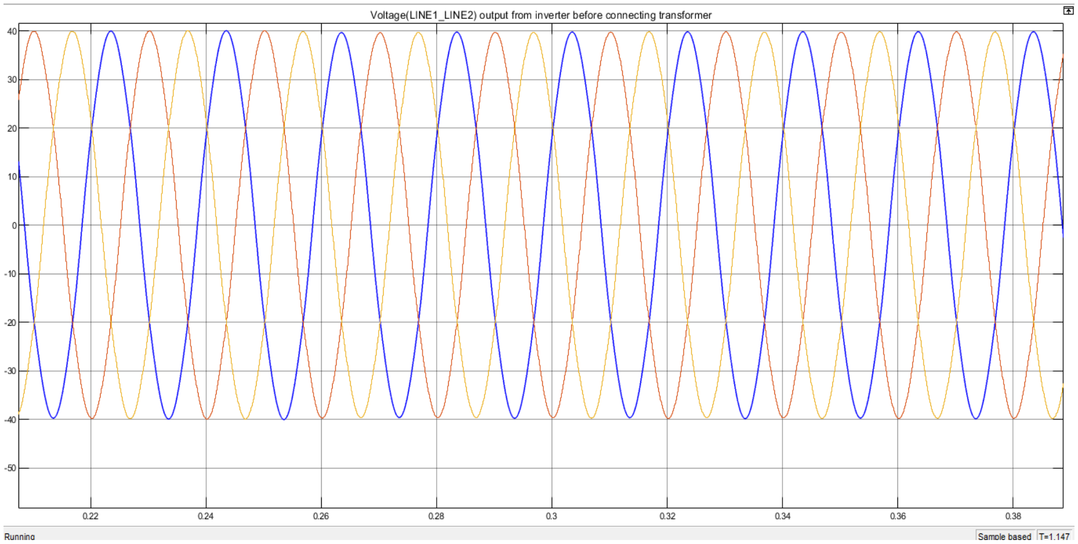

Fig. 20. Inverter output before connecting transformer

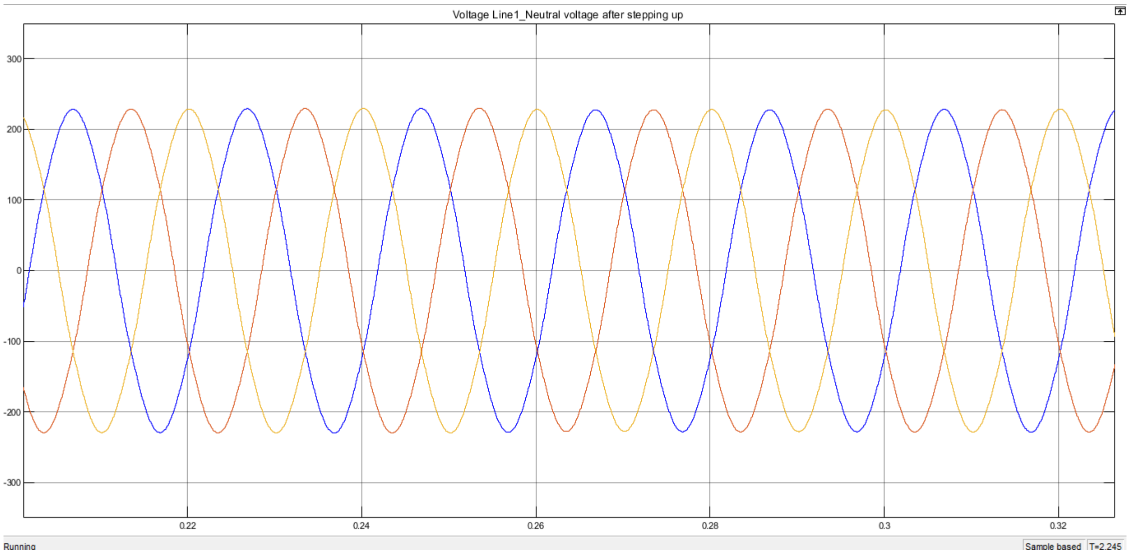

Fig. 21. Inverter output after connecting transformer

Table 5. Input torque

Time	**5sec**	**10sec**	**15sec**	**20sec**	**25sec**
Torque	25.59Nm	12.79Nm	6.39Nm	12	9

4.5.1 Motor torque

Torque is calculated using the eq.1 and gives the following results:

$$T = 9.555 \times \frac{7.5 \times 10^3}{2800} = 25.59 Nm$$

The machine can be started by changing the frequency as the power supply is from the inverter and it has that ability to start the machine as a soft starter.

On a machine which is supplied by human being, the torque is not constant. It is always changing depending on what they are feeding and, on the place where they are getting them.

Consider a feeding of the machine as follow in the Table 5.

To have the result on the machine, there is a requirement of the load and in this case, it is the grains supplied inside. The load here is in terms of torque (Nm) that the motor is required to develop so that it is possible to transform grain into power(flour).

The torque in the Table 3 is the input as the load of the machine to show its characteristic when it is running at no load and when it is having the grains inside.

The above graph is exactly the presentation Table 3 of the load that has been inserted in the machine. At starting the machine had no load and after 5sec the grain was allowed to inter inside. After 10secs, the grain has been reduced to a given value and again after 15 secs reduced to a low value because they were about to finish in the hopper.

At 20sec the hopper is almost empty and the machine has to be stopped to avoid the consumption of electricity for nothing.

To understand the work the motor is doing here, let's have a look at the speed characteristic when the load is changing inside the grain mill machine.

4.5.2 Speed characteristics

By running the system and recording the speed with respective time, the following speed characteristics is obtained.

By changing the load(torque) speed will be affected directly.

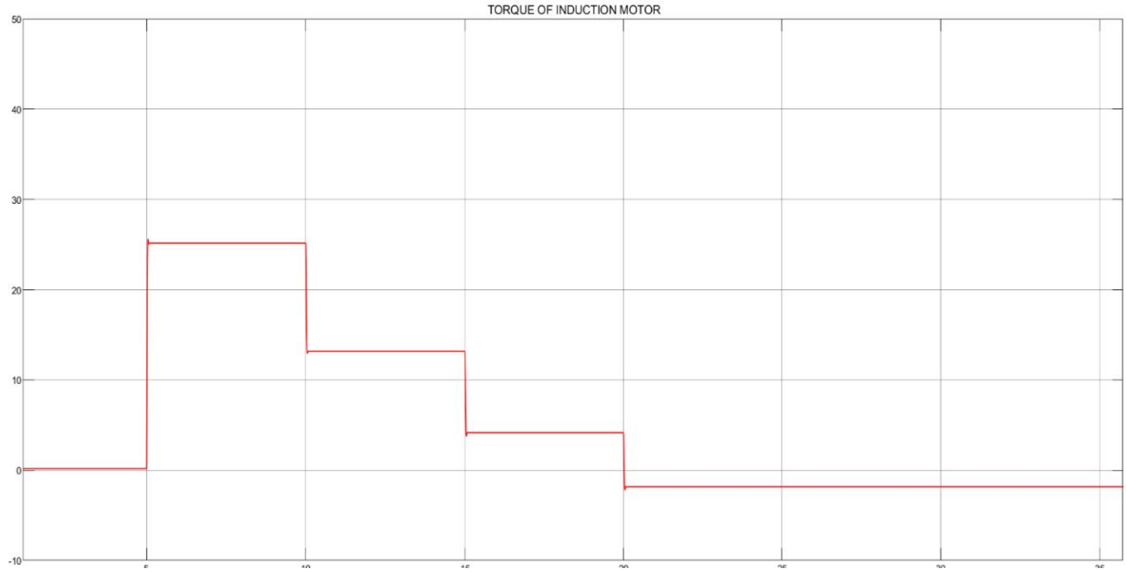

Fig. 22. Load Torque characteristic

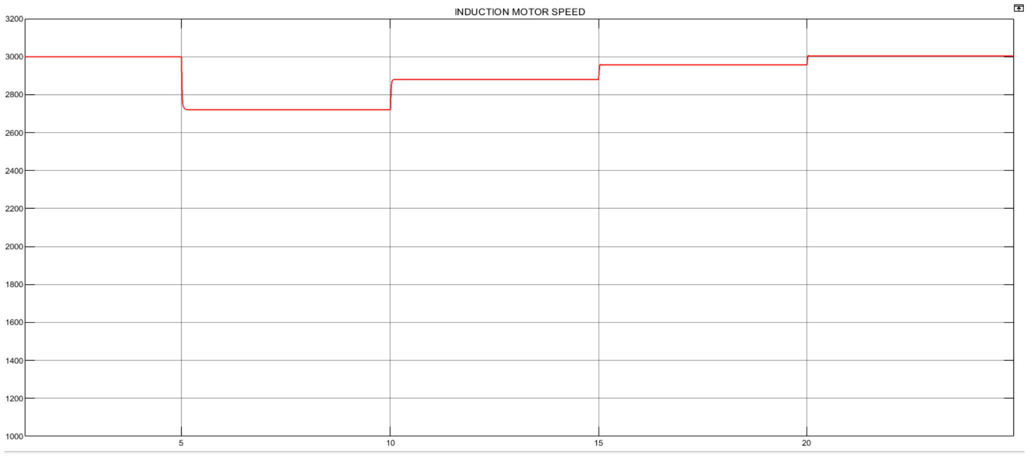

Fig. 23. Speed Curve

At no load (when there is nothing inside the machine), the machine is running at maximum speed near which is around 3000rpm.

Between 5seconds and 10 seconds the grains were allowed to inter inside for transformation in this case the speed was decreased because of the opposition of force of the machine with the mass of the grains where the last value became around 2700rpm. By reducing again, the quantity of the grain entering in the machine the speed is affected again between 15 to 20 seconds where the speed has increased near 2900rpm.

The speed of the machine is affected by the quantity of the grain entering in the machine therefore it is very important to control the input of the machine in the hopper to avoid the overloading of the machine.

5. COST ANALYSIS

5.1 Energy Demand Study

For determining the capacity of a solar home system project, the estimation of energy demand has to be taken into consideration. In grain mill machines which are used for commercial purpose, the machine which can try to have efficiency in terms of production and supporting the overload must have the induction of at least 7.5kW and able to produce an average of 300kg of flour per 1hour. In addition to this also to supply a surrounding community for home consumption especially lighting. It is about 20 families each of 6light bulbs of 20W used 6hours corresponding to 2400W or 2.4kW.

5.2 Financial Analysis

This part of the project is going to help us to analyze the status of the project financially and the end-use services beneficiaries.

Different financial aspects of the project are to be taken into account for exploring financial viability. Among them there is the cost of the project, projection of income and expenditure, and financial feasibility analysis.

5.2.1 Project costing

The total cost of the project includes all material and installation cost. To obtain this the market survey is done to get the cost of PVs, Power conditioning unit, cables, and support structure. In addition to this there is also transport and manpower until the project is able to run.

The cost of all those items was obtained on an online market including shipping and also compared to the Rwanda market.

The label market of Rwanda also has influence in estimation of cost of the man power and the required number of days that the system can be installed. If there is a gap on cost estimation by becoming lower that it was planned, the contingencies compensate to the system.

5.2.2 Material required and their corresponding cost

The total cost of the project design of an off grid solar grain mill is 29,690US$ so that it will be able to run the machine and also to supply electricity to 20surrounding families for home lighting.

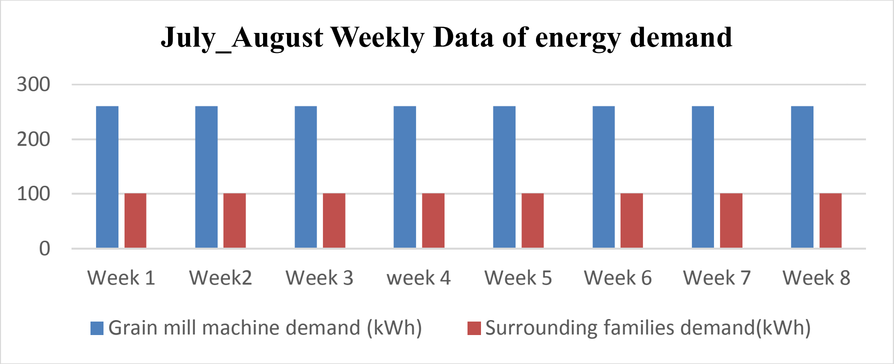

Fig. 24. Power demand

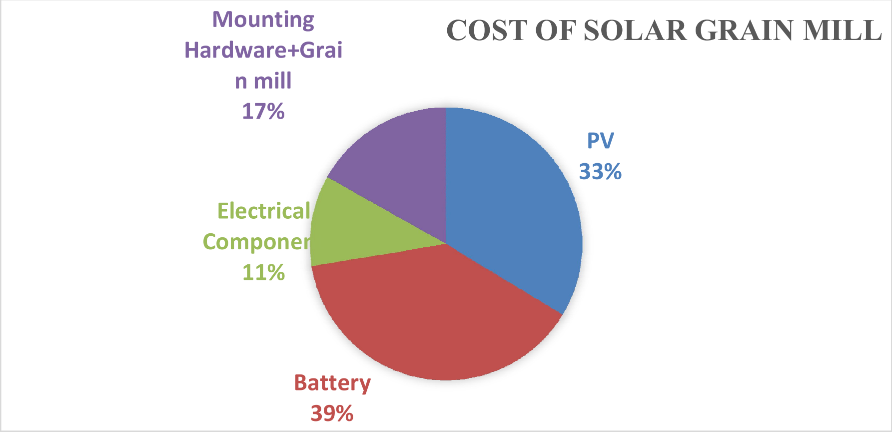

Fig. 25. Overall cost of the plant

5.2.3 Projection of income and expenditure

After running the system, it starts to produce some amount of money to pay workers who are under the survey operation, buying screens whenever they are needed and other maintenance related activities as they can be required. The income generated is based on the agricultural product which is there for servicing (to be milled). The survey done on two different sites, show that on average site A had 600kg per day and on site be has an average of 650kg. In addition, there power consumption for home lighting of 20surrounding families of 2.4kWh per day.

Considering the cost of production of kg of floor to be 50Rwf and unit cost of electricity to the surrounding community to be 85Rwf per kWh.

$$\text{Projection income Daily} \\ =\text{Daily income}_{mill}+\text{Daily income}_{community} \tag{35}$$

The projection income includes taxes and manpower on the grain mill. So, it contains the expenditure.

$$\text{Expenditure=Expenses}_{\text{worker}}+\text{Tax+ Contingencies}$$
(36)

This is done monthly.

$$\text{Daily Projection Income} \\ =\frac{650kg}{day}\times 50+\frac{2.4kWh}{day}\times 90=32,716Rwf$$
(37)

$$\text{Monthly Projection Income} \\ =\text{32,716Rwf}\times\text{30days=975,216Rwf} \tag{38}$$

Let Taxes be 50,000Rwf and Manpower be 40,000Rwf per month

$$\text{Expenditure=50,000Rwf+40,000Rwf+100,000Rwf} \\ \text{=190,000Rwf} \tag{39}$$

$$\text{Monthly Income=975,217Rwf-190,000Rwf} \\ \text{=785,216Rwf} \tag{40}$$

The total monthly income of the project is 785,216Rwf corresponding to $810 and $9,720 per year.

Here it is possible to calculate the payback period of the project when knowing the investment of the project whenever implemented.

From the table of proposed materials of project and corresponding cost, the total cost of the project is 29,690US$ and the annual projection income is 9,720US$, the payback of the project is expressed as:

$$\text{Payback=}\frac{\text{Total investment}}{\text{Annual income}}\Rightarrow\text{Payback} \\ =\frac{\$29,690}{\$9,720}=3.05\,years \tag{41}$$

Considering the life span of PVs to be 20years, for battery to be 5years and power conditioning to be 10tears, the project is technically feasible due to the availability of sunshine on both site and also economically feasible because the life span of the project is greater than payback period of the project. It is possible to get back money invested in the project before it gets expired.

6. CONCLUSION

This paper was the proof-of-concept effort to study the design of an off grid solar grain mill machine associated with the home lighting system of 20 surrounding families. This effort resulted in the intelligent distributed production of electrical energy from solar radiation, thereby raising overall power generated in a country and reduction of fossil fuel consumption toward protection of the environment.

The system components designed included selection of PV panels, and the electromechanical equipment such as PVs, charger controller, energy storage and grain mill machines.

This project is designed to generate 13.568kW for which 7.5kW is to be used for grain mill machine to provide services in remote areas that fall from national grid and the remaining for home righting of surrounding communities.

This off-grid solar power plant has been analyzed based on different parameters including technical, economic feasibility study and plant life cycle. The result has shown that the project is technically feasible based on the irradiance available and as compared to the PV modules characteristics. It is economically feasible based on its payback period which is 3.05years and with life cycle of battery of from 4 to 5years. Although, this system will reduce the use of fuel which is used for agriculture activities like small scale agro-processing and irrigation by the use of diesel engines. These small internal combustion engines have an impact on the environment and they can be replaced by solar powered systems for environment protection purposes and operating cost reduction.

Whenever it is impossible to use the battery due to different reasons like high cost of the project, the system can still work but providing the services of grain mill to customers during day time when sun radiation is available and stop working at night. Development of many solar off grid power plants can reduce the electricity shortage and make scale savings if carefully planned.

Due to the needs of high-power demand in our country which leads to the use of thermal power plant particularly internal combustion engines that are emitting high amount of CO in the air (causing the environmental pollution), we do recommend the following:

- Internal combustion engines should be replaced by solar power systems.
- Leaders in charge of energy sector should think about renewable energy resources especially solar.

DISCLAIMER

The products used for this research are commonly and predominantly used in our area of research and country. There is absolutely no conflict of interest between the authors and producers of the products because we do not intend to use these products as an avenue for any litigation but for the advancement of knowledge. Also, the research was not funded by the producing company rather it was funded by personal efforts of the authors.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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