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Design and size an off grid solar power system

Case study: Musenyi health center located in Bugesera district/Rwanda

A final thesis presented to the academic department of Science and Engineering in partial fulfillment of the requirements for the degree of Bachelor of Science in electrical engineering

ATLANTIC INTERNATIONAL UNIVERSTY

HONOLULU, HAWAI

March 2020

Acknowledgements

Frist and foremost, I would like to express my thanks to Almighty God to have been with me through the academic journey and before. Without God's guidance and protection, the thesis would be achieved only the dream.

The special thanks to be addressed to my two successive academic advisors: Dr Franklin Valcin and Dr Edward Lambert. They have been there to provide me guidance with the right direction to do the best academic works and I really recognize how much you supported me through this patch of the academic achievement and to the final thesis development, with you everything dealing with academic matter were figured out since the beginning of the program at Atlantic international University.

Lastly, my sincere appreciation and thanks go to my beloved wife Angelique, my daughter Gianna, my parent and siblings, without their prayers and encouragement, it would be impossible to follow up the higher learning education, your input has been recognized.

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List of abbreviations

AC: alternative current

Amph: Total ampere-hour of battery bank required by system load

Amph/string: minimum ampere-hour per string in battery bank

DC: direct current

DOD: Depth of discharge

DoT: Days of autonomy

Eb: Energy storage in battery bank

E/Day: Energy per day

Et: Total ac energy required

I: current

Ib1: Current flow in single string

Ib2: Current flow in overall string to charge controller

Ic: current flow in charge controller

KW: Kilowatt

KWh: Kilowatt-hour

MPPT: Maximum power point tracking

MW: Megawatt

Nbs: Number of battery in series

Nbp: Number of battery in parallel

Nms: Number of module in series

Nmp: Number of module in parallel

Nt: Total number of modules

Pm: Power available on solar array or watt peak on solar module

Pm/day: Power available per day or peak watt on solar module per day

PoP: power of single module

PMW: Pulse width modulation

PV: photovoltaic module

REG: Rwanda energy group

Vs: System voltage

Vob: voltage of single battery

Vd: voltage drop in system

Tm: Temperature multiplier

TV: Television

Abstract

Nowadays, more country of Africa are looking for the way to develop in field of energy need, however some have been facing the challenge of power cut or grid failure due to the lack of sufficient energy to power their citizen which in return affect the daily activity of industry holder to produce the final product that will later go to the final consumers. In fact, there are various way the electricity can be generated and in Rwanda, where this bachelor thesis is taken into consideration, most of energy derives from potential in water, methane gas (natural gas), peat to power, diesel based generation and solar power system.

Today, Rwanda government is targeting to overcome the above issue of power cut and grid failure by facilitating the stakeholders and other private companies and other investors to invest in energy section based on power generation in all corner of energy development to boost the current power capacity from 224.6MW corresponding to 53.5% today and move to capacity of 554MW by the end of year 2024 which is corresponding to 100% to connect all the citizen of Rwanda. It really requires the great effort to hit the target, and all means to generate electricity and able to supply the citizen is on top harvested to the existing energy, that's why this project of solar system should come on to contribute on the overall increase in energy possession of the country.

The bachelor thesis aims to work out the design and size an off grid solar power system based on load profile where the health center of Musenyi is taken in consideration to overcome the challenge it has of supplying its current load .There, everything regarding an off grid solar power system will be worked out and the way of designing can help for any other engineers to design and size an off grid solar power system based on load profile. In assessment of current load profile, the issue of failure of a solar power system of Musenyi will be sorted out with recommendation and future extension about the existing solar power system will be sort out there and upon the end, loading procedure will be declared to maintain safely and healthy the current or the next off grid solar power system.

1. Problem statement on the current off grid solar power system

Basically, off grid solar power systems are designed in similar way, and the only difference would be how the choice of equipment would be randomly selected depending upon the load profile. In fact, when the load has been determined, the number of modules, size of battery bank, charge controller capacity and inverter's capacity will be no doubt selected according to the current currying capacity of each other by referring on the calculation worked out. That are main the tasks the thesis will be handling and assess the better choice of various equipment according to the requirement of the load of solar system.

1.1 Problem statement and discussion on the final project

Specifically, this final thesis holds on the design and size of an off grid solar power system of Musenyi health center located in Bugesera District, Eastern province of Rwanda. The current problem that off grid solar power system of Musenyi health center has, is to fail supplying the entire current load in efficient way and so far, the purpose of this bachelor thesis is to assess the current load and make decision where it is possible to work on the existing solar system by doing necessary correction on or redesign the new solar power system to make sure that the performance and reliability of power is available all the time without failure or disconnect some of the load.

During site inspection, the problem observed that needs to be solved is that the existing load of the above health center does not match with the size of the solar array which requires to disconnect certain load and leave others load continue to be supplied. That issue will be solved by doing further load analysis and reveal why solar array were not effective to hold on supplying the entire load and provides necessary measures to take out.

1.2 Research goal and environmental impact on the selected area

The goal of doing the research on Musenyi health center off grid solar power system were to monitor if the current solar system donated by the government of Rwanda is still working in efficient way and reliable to hold on the supplying the load without problem as it was previously performing. In addition, the health center has a diesel generator which complete the solar system if there is trouble in solar power supply, it serves as back up and used when solar system is completely isolated and that are the main reason to assess and stick on the power availability at the health center all the time.

However, one of the main use of generator, should be of charging the battery bank when solar system is not able to fully charge the battery bank, and even serves as back up as previously said, but it should be used less as possible to reduce fuel used once the solar system is working in effective way, this will save money and keep and environment clean as well. Normally, an important thing to quote there is that, the usability of diesel generator produces fume when operating and contribute much more on the atmospheric ozone layer destruction and this should be taken account and considered to reduce as soon as possible when off grid solar power system will be fully operating and shortly, solar system will be more effective than before after revision and full assessment of the root cause of the continuous failure.

2. Background on solar power system in Rwanda

The country of Rwanda has spread out the great opportunity to the stakeholders and shareholders to invest in energy sector with purpose of increasing the generation of power in the country. The energy need increases as citizen also request it much more, it is foreseen that energy plays an important role in various aspect of the country's development such as medical treatment, small and big industries, factories, and other field where electricity depends on and so that the availability of it play an tremendous aspect to the overall development of country as well as the living condition of the population living the country. In fact, power is generated by using various mean. Here in the thesis, only the power generation based on solar radiation will be focused on as Rwanda is among the best countries of Africa that have better solar irradiance of average of 5.4KWh per m2 daily basis which shows the solar potential in the country and prove the feasibility project of more solar power system in the country on large scale than today.

2.1 Why solar power system is becoming popular in Rwanda?

Rwanda has become the best country to invest in since it started facilitating the private sectors to invest in various field like education, infrastructure, health services, and agriculture, manufacturing and other many more such as mining and energy sector, the thesis intended to count on energy where solar power system considered were presenting the average of 5.7% in the year 2017 by comparing the current generation with the other source of energy generation. Today, solar system on small scale are being used by part of the citizen to supply their home appliances such as light, radio, TV , charge telephone and other equipment that does not consume more power.

In fact, there are two types of solar power systems based on electricity generation in Rwanda, the one is grid tied solar power which is commonly used for bigger solar power system that are connected with grid, in this mode of generation, the owner of solar system has the ability to supply himself and the excess of generation is fed back to the grid. In this type of solar system, a special meter is installed to track the flow of power in two directions to measure how much of energy is fed to the grid and again how much of power the grid has fed to the owner of the solar power system during the night when the sunlight is not available, this type of solar power system does not possess the battery bank and that is the main reason that during the night, the owner of solar system should get supply from the grid and this is less used as it requires power of the grid to be connected with. Agahozo shalom is one of the biggest grid tied solar power system in Rwanda.

However, there is another interesting type of solar power system that is not connect with the grid, that type of solar system is known on off grid solar power system which is the only one the final project will deal with and is the most popular as it not connected on the grid, simply the project is more beneficial for the population living in the remote area where the power of the grid is not available or difficult to access. Moreover, Rwanda is reinforcing to supply electricity to the citizen living far away from the grid with the mini solar power system in different village so that, the target of energy supply to the citizen of 100% by the year 2024 is completed. This target is possible with the implementation of more off grid solar power systems to compensate the power dispatch in various village where the power of the grid is not available or is difficult to access, that is where the off grid solar power system find application in mass with many citizens and specifically, the case study is taken in Eastern province of Rwanda, Bugesera district.

2.2 Some of cause of failure of an off grid solar power system

Most of the issue that many off grids solar system faces are to have been undersized or bigger load application which in the future affect the overall efficiency of the entire of solar power system, and to overcome that challenge, the only secret behind is to carry out the load study analysis that an entire solar system will have to supply and accordingly all other size of the equipment will follow up. Without that, designer do nothing and that is the first important step to undergo with solar power system.

To design an off grid solar power system requires to pay high attention, the site overview where solar is not at reasonable irradiance may cause the failure of the entire solar power system and the output of photovoltaic system depends on how strong the solar radiation are falling on the solar module, anything that may shade the module and prevent it to receive at maximum the fall of solar radiation will affect much more the power output, and so that to overcome above issue, the solar module should be placed at place where it is freely able to capture the sunlight without shading effect, however , most of modules are place on the roof of the house, if the designer is willing to have off grid solar power system, the civil engineers and architecture of the building may do their work and considering the slop of roof to the best place to maximize the solar energy. If the above mode of positioning of solar modules are not considered, high risk to have system with low efficiency is booked up and will affect the overall performance once commissioned for operation.

3. Thesis statement and research methodology

Today, the total capacity of 12.08MW of grid connected solar power system often known on grid tied solar power system are available in Rwanda. There is still long journey to go with solar power system on either off grid or grid tied solar power system. However, the power derived from solar system would be the better solution for the Rwanda citizens to accelerate the power access as targeted by the government.

The reason behind the usability of solar power system is that it is a kind of renewable energy that does not contribute to the atmosphere pollution and is more ecofriendly type of energy that Rwanda has than other sources of energy. Moreover, anyone living in the remote area, where the power of the grid is not available, the off grid solar power system is the best solution than others, because it is cheap in term of usability but looks expensive in term of cost of materials and equipment, installation and but the running cost compared to the power of the grid and or if the generator is used to supply the same load.

3.1 The outcome on thesis statement and development's concept

However, the thesis statement intended to carry out research on off grid solar power system of Musenyi health center and investigate deeply the major cause of failure and provide the reliable solutions. The questions to answer here are: Is the off grid solar power system of Musenyi health do what it was intended to do? If no what solution the thesis development would recommend so that the previous off grid solar power system perform in efficient away? And all about this will be the overall questions to overcome the issue behind and work out in deep the project in right way with accuracy.

3.2 Purpose and objective on doing research on the final project

In fact, there is no project implemented without carrying out research to see whether project is feasible or not, and formulate the hypothesis to be tested many time to drive on the final successful result and would not be ignored to maintain the sustainability of research that leads to the reasonable result at the end. The main purpose to have been chosen this project was to investigate, analyze load profile, look up on various equipment in the existing off grid solar power system and provide feedback on their performance.

In the meanwhile, after site visit, it has been observed multiple issue encountered in the design of Musenyi health center in Bugesera district, located in Eastern province of Rwanda:

1. Solar array arranged at place where it cannot maximize the sun ray
2. Load has grown systematically and solar array cannot handle it
3. Poor maintenance on the entire off grid solar power system which lead to breakdown of some part of the solar system,
4. Some of photovoltaic modules and cells are no longer performing and need replacement for better efficiency.
5. Charge controller of PWM and do not perform in effective way
6. Inverter size and maintenance and load handling have been serious issue to sort out with the new choice of inverter able to handle current load
7. Battery bank has been down operation when the sunlight is not available, which simply mean that, no autonomy is out here to run electrical appliances.

All above issues lined up out there must be cleared with new off grid solar power designed according to the current load profile, and will take care of design of various parts to overcome the existing issue which has triggered the breakdown of the solar system.

4. Strategy and technique in design of Musenyi off grid solar power system

In this project dealing with the solar power system of Musenyi health center will be designed to match the load with the size of the array taking care of various equipment and component necessary to avoid further failure, and that why this final project intends to work out on all the part of the solar system to determine accurately the size of the entire solar system performance and effectiveness. It will require first to understand the basic operation of solar power system and here down is what is going to be reviewed as far as solar power system is concerned.

4.1 Introduction on solar energy, basic principle and application

Looking on how renewable energy is advancing in various application of engineering, however, the solar energy that reaches the earth is abundant and using different scientific method, it is possible to convert the energy of the sun in other useful form of energy such as electricity, heat energy and kinetic energy. It has been proven that overall solar energy that hit the earth is about $1KW/m^2$. That kind of solar energy is the converted into electricity based on the technology of semiconductor devices that operate under condition that, when exposed on solar energy, they have capability of generating the voltage across the terminal. The special devices are known on silicon diodes known as photodiode and are connected together in series and parallels to increase the voltage and the current respectively to form what is commonly as photovoltaic panel or solar module. Here down is an example of solar cell made up of photodiode able to generate electricity once it receives or exposed on sunlight.

Figure 1: Single solar cell that form solar module

Specifically, there are many reason that solar energy is the best to deal with, and it find applications in various field such as satellite applications, industrial zones, car based solar innovation and other more. Here down is an example of solar module in which various solar cells are connected in series and in parallel to increase the voltage output and current required to deliver the specific power to the connected load.

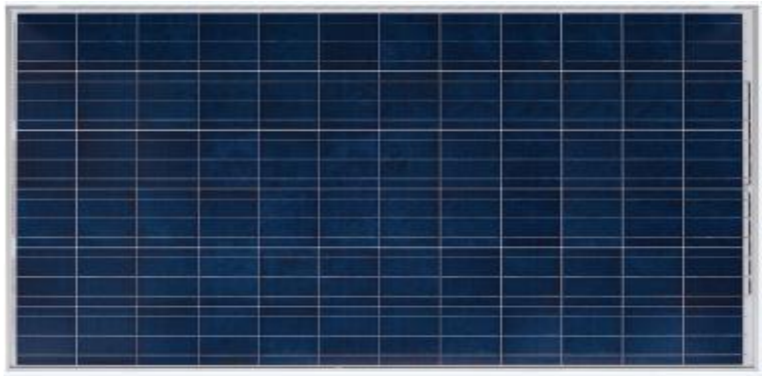

Figure 2: Solar panel made up of more cells to increase voltage and current

4.2 Structure of an off grid solar power system

Obviously, the main structure of an off grid solar power system is made of 6 majors' equipment that will be exercised to provide an effective solar power system, where every equipment will be sized according to the power flow as well to the current currying capacity at each stage and considering the cable that connect every equipment.

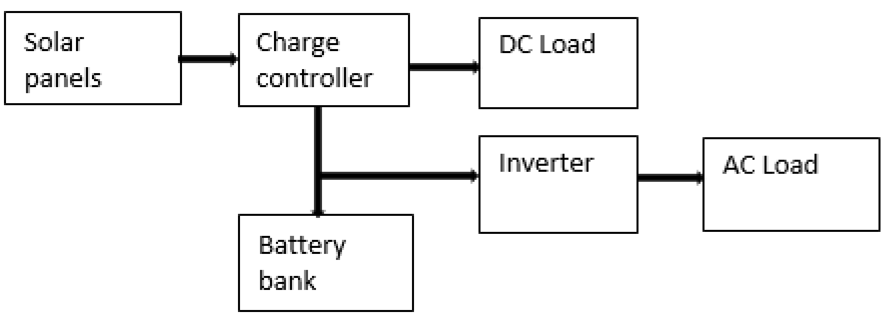

Figure 3: Structure of off grid solar power system

The above solar power system structure shows the various part which will be discussed during the design of the solar system, regarding the site, Bugesera is the best place for implementation of the project is it was really done before, it is the area with cumulative good solar irradiance when taking review on global yearly and daily solar potential.

4.3 Site overview and data gathering for sizing off grid solar power system.

In this final project, the site visit and data gathering was the major step to conduct the root cause of the failure of the solar power system and carry out the reliable off grid solar power system that is able to handle the current load of the health center. To do so, there are factor to consider with mathematical approach to provide the reliable off grid solar power system.

As seen on the site, the existing solar power system is not operational because of multiple issue already listed, but the major and big cause is that, the load has increased significantly such that the solar array is no longer able to deliver power at full capacity and other problem which is serious is that the battery bank has been affected much more due to lack of maintenance and during rainy season or night, it cannot withstand the connected load. The preliminary data needed is the load characteristic, in this way, the designer of solar power system should have to define the type of load, and how much of time (duration) load need to be connected as indicated in the table below:

Type of equipment	Quantity	Rated power(W)	Total power(W)	Time used per day(h)	Energy consumed per day (Wh)
Flat TV	2	100	200	5	1000
Water heater	1	200	200	2	400
Water pump	1	150	150	2	300
Lighting	8	10	80	7	560
Refrigerator	1	100	100	7	700
Air conditioner	1	1000	1000	3	3,000
Washing machine	1	200	200	1	200
Lab equipment	3	100	300	5	1,500
Computers	5	30	150	3	450
Total power	xxxxxxxx	xxxxxxxx	2,380	xxxxxxxx	xxxxxxxx
Total energy	xxxxxxxx	xxxxxxxx	xxxxxxxx	xxxxxxxx	8,110

Table 1: Load profile record of Musenyi health center

In the above table shows the current overall power consumption of Musenyi health center with the respect of time (duration) that every equipment is supposed to be connected on the circuit. Hence, the overall energy per day calculated is 8,110Wh/day or simply 8,11KWh/day. However, that power is considered if the equipment are connected at respective time interval and if they are all connected at the same time, the overall power is about 2,380W or simply the power of 2,38KW.

4.4 Overall solar radiation in Rwanda

While Rwanda has adequate solar energy potential to support energy demand, it has been therefore been an important opportunity to harness that type of energy to find the solution to the energy shortage and environmental degradation the country faced in the recent time. However, solar energy is the best effective and economic resource to have using to generate electricity as good as possible. It has been proved that overall solar energy radiation in Rwanda specifically in Bugesera district and Kigali found on the average of 5.4 KWh/m^2 which is likely to mean that every meter square, the solar energy possession of 5.4KWh in the area of one meter square and can reach out 4.5Kwh/m2 in the cloudy season, this is huge power that Rwanda is about working on where an investing company known on Agahozo shalom located in Rwamagana district / eastern province of Rwanda has been operating since 2015 by installing the capacity of 8.5MW of grid tied solar power system which testify the availability of doing business based on solar power system and today, there are various solar power system which are tied with grid as well other off grid just like the case our final project is dealing with. In developing the project, the data of 5.4KWh/m^2 solar irradiation energy will be taken account in sizing the solar array required to supply the connected.

4.5 Consideration of overall efficiency factor and number of modules required

The efficiency of solar power system depends on several factors that affect the output of solar modules, however, this can be rectified by considering the factor 1.3 on the energy calculated to determine the solar modules required. Hence, the overall energy used considering the oversize factor will be:

$$\mathbf{E/day = 1.3 \times 8.11KWh/Day = 10.543KWh/Day}$$

As already previously seen, the solar radiation in Rwanda is about 5.4KWhm2/day, which simply expressed that the solar radiation is abundant at average of 5.4h a day in every unity meter square where a solar module is exposed without shading, hence, we are now able to work out the watt peak (Wp) that panel will require to deliver the full output power once receive the solar ray. Therefore, the total watt peak (Pm/day) required by solar array can be determined as follows:

$$\mathbf{Pm/day = \frac{Energy\ available}{Solar\ hour}/day\ (1)}$$

$$\mathbf{Pm/day = \frac{10.543Kwh}{5.4h}/day\ = \frac{1.954Kw}{Day} \approx 2Kw/Day}$$

From the above calculation, it is clear that total watt peak required by the solar array or photovoltaic solar system is about 2KW and after that, it will be simple to get the number of modules once the total power on the solar power system is already calculated and what is remaining there is to select which type of solar modules is required for the above characteristic of load requirement.

However, the task here is to choose the modules according to the power output, if the choice is made on modules with low power output, it will requires more number of modules and the connection will be complex as series and parallel connection will be required, and so that, the choice will be done by considering the module of higher power output to maintain at least the minimum string of series as they often cause the problem of loss, where if for example one of the series modules is shaded or damaged, it will cause the other to stop out delivering the power. Let's consider the solar module of SD that has the electrical characteristic (250Wp) with the short circuit current (Ish) of 8.7A and the terminal voltage of 24V

It is now possible to determine how many numbers of solar panel according to the required panel selected randomly:

$$\mathbf{Nt} = \frac{\mathbf{Pm}}{\mathbf{PoP}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(\mathbf{2})$$

$$\mathbf{Nt} = \frac{\mathbf{2000W}}{\mathbf{250W}} = \mathbf{8}$$

So, the eight solar modules are required to complete the off grid solar power system and do the determination of series and parallel strings to fulfil the requirement of the system.

4.6 Solar module's configuration

In fact there are two type of configuration to be made here, one is parallel connection and the second is series connection, and the advantage behind is to design the system to match with the device rating voltage, however, the system voltage to which the solar system will operated according the equipment and design procedure is to be 48V, so far the connection of modules will be made such that are possible to adapt to the system voltage.

4.6.1 Series module's configuration

As previously calculated that, the total number of modules is eight, the selected modules are of 24V, and the solar system voltage is 48V, we would make arrangement of connecting them such that the 2 modules be connected in series to increase the solar module's voltage to 48V required by the entire solar system. The advantage here to wire the solar modules in series is to increase the voltage and keep the current flow the unchanged. Here down is an equation to apply to get the number of modules required

$$\mathbf{Nsm} = \frac{\mathbf{Vs}}{\mathbf{Vob}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(\mathbf{3})$$

$$\mathbf{Nms} = \frac{\mathbf{Vs}}{\mathbf{Vob}} = \frac{\mathbf{48V}}{\mathbf{24V}} = \mathbf{2}$$

4.6.2 Parallel module's configuration

To maintain the system voltage unchanged, the solar modules will be connected in parallel, but the current delivered by a set of modules connected so will be increased or added together. So far, our designed solar power system will have 4 strings panels connected in parallel as required by system configuration. Here down is the equation to work out the number of modules required in parallel.

$$\mathbf{Nmp} = \frac{\mathbf{Nt}}{\mathbf{Nms}} \ldots\ldots\ldots\ldots\ldots\ldots.(\mathbf{4})$$

$$\mathbf{Nmp} = \frac{\mathbf{Nt}}{\mathbf{Nms}} = \frac{\mathbf{8}}{\mathbf{2}} = \mathbf{4}$$

4.6.3 Overall solar module's configuration

In fact, connecting solar modules in series will add the voltage to a specific working voltage required by the solar system to charging the battery bank, while connecting solar panels will hold on adding the current flow from solar modules on charging the battery bank. However, the above two configurations will help on determining the total current from the solar modules to charge the battery bank on the specific system voltage required by off grid solar power system. So far, the power generated by solar modules is constant regardless to the connection considered, only the series and parallel will change only voltage and current respectively.

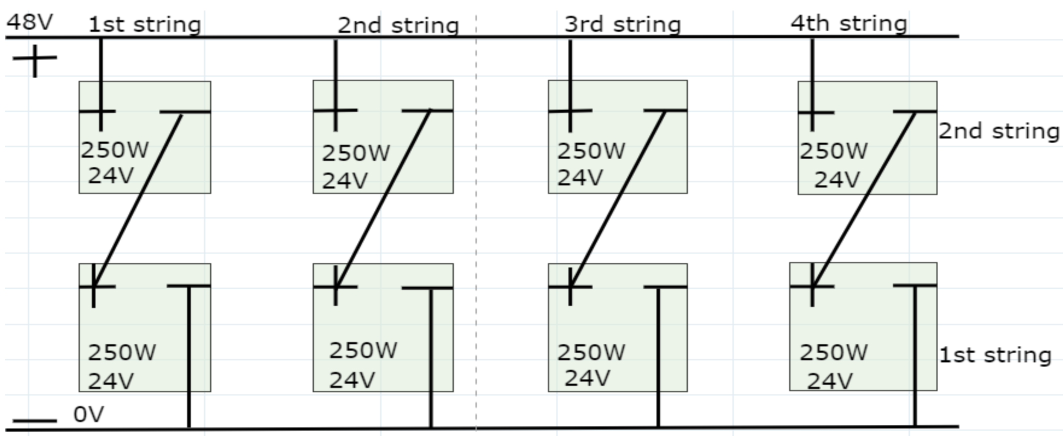

Figure 4: Solar module configuration overview

Here above is the wiring arrangement of solar modules connected in series and in parallel, where the negative terminal of solar panel labeled 1 is connected to positive terminal of solar module labeled 2. The two modules have now the only two terminals (negative and positive) connected on the main bus bars also labeled negative and positive. Further details on configuration can be seen on the figure5.

4.7 Size charge controller matching with the load

Normally, the sun is variable a day, week or a month and other factor such as temperature, cloud and or rain season are the major key point that affect the output of solar power system. However, charge controller is introduced in off grid solar power system as solution to regulate the amount of flow of electric power delivered by solar module array to the battery bank. So far, charge controller will be in the circuit to prevent two major things:

1. prevent battery charge overflow when the sunlight is abundant in a day, this will allow the battery bank to breath by dumping down the charging current and will too prevent the overheating of the gas inside the battery bank.
2. prevent flow back of charge from battery bank to the solar array in dark period or night, this is critical action to choose the right charge controller that is able to perform in such condition and rate it correctly to avoid further damage

4.7.1 Pulse width modulation (PWM) charge controller

Power width modulation (PWM): This type of charge controller on the principle of modulating the waveform of voltage and current required by the battery bank, this type of charge controller has less efficiency compared to MPPT and it’s quite difficult to optimize the voltage difference and this a negative impact on the overall efficiency of the entire solar array, and so far, this type of charge controller is not expensive at all. The Health central has this type of charge controller which so far has been unable to capture and optimize the overall efficiency as well as other equipment in conjunction were affected.

Figure 5: PWM Charge controller

4.7.2 Maximum power point tracking(MPPT) charge controller

Maximum power point tracking (MPPT): this type of charge controller is the best one to choose because of multiple benefit integrated with, some of them are that it has very good efficiency where it can optimize the dc load and the voltage difference of the entire solar power system. Regarding the price, this type of charge controller is quite expensive compared to the pulse width modulation (PWM). This MPPT charge controller is the one I recommend to use in the new designed solar power system to keep the effectiveness and better performance.

Figure 6: MPPT Charge controller

In fact, we can see how much the charge controller is important in off grid solar power system and the choice of it is a key critical element to consider in order to have solar system with good efficiency as matter of that equipment in conjunction with other are well selected. Upon the calculation made above, it is too possible to work out the number of charge controller based on the current carrying capacity that charge controller is allowed to hold on. Let’s go back to the previous Watt peak required (Pm) by the solar modules and find how much number of charge controllers needed to sort out in accordance to the value of current flowing from the solar array to the battery bank. And note that in the design process the voltage of 48V is selected in compliance with the equipment needed to complete the off grid solar power system, it will be common for battery bank as well inverter and solar panels. Without further ado, let’s go through calculations:

$$\mathbf{Ic} = \frac{\mathbf{Pm}}{\mathbf{Vs}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(\mathbf{5})$$

$$\mathbf{Ic} = \frac{\mathbf{Pm}}{\mathbf{Vs}} = \frac{\mathbf{2000W}}{\mathbf{48V}} = \mathbf{41.66A}$$

It is worthwhile to choose the charge controller of MPPT that will be able to handle that flow of current (41.66A) to charge the battery bank with the specific operating voltage. Remember that charge controller has two important roles here of regulating the voltage of the solar array to the required nominal battery bank voltage and prevent the flow back of power from battery bank to the solar array when the sunlight is not available.

Here down is the characteristic of charge controller that meets with our sized solar array to charge the battery bank on the specified working voltage.

Type	MPPT Charge controller
Brand	Outer back Power
Series	Flex Max series
Max current (Im)	60A
Adjustable operating voltage	12V,24V,36V, 48V
Temperature at rated current	40ºC(104ºF)
Max PV array voltage (Vdc Pv)	150Vdc

Table 2: Charge controller specifications

In fact, there are other type of charge controller that may act in the same way as, but the choice of MPPT should respond to the minimum requirement such as operating voltage, maximum current of solar array and maximum PV array voltage regardless to the brand manufactured the MPPT charge controller.

4.8 Size battery bank of solar power system and back up required

All off grid solar power system must have a battery back up to keep the solar system running when the sunlight is no longer available, this is the critical factor to consider with accuracy when designing an off grid solar power system. So far, the solar power system of Musenyi has also to be designed with good storage capacity to sustain the availability of the power to the connected load during the night or rainy season where sunlight is not stronger to charge battery to full. However, there is number of days that a solar power should run without solar radiation and the days required would be determined how many number of batteries required of which capacity and how many days can the system operated on that batteries without shortage , that factor is known as the autonomy.

Simply , days of autonomy is the number of the days that an off grid solar power can remain supplying the load on the battery bank without any other source of energy, the autonomy is sometimes called battery bank multiplier and can vary from region to region depending on the availability of solar radiation in the selected area. In fact, Rwanda is among the country with strong solar radiation and in the design process, the autonomy of 3 days will be considered to size the battery bank required by the off grid solar system,

4.8.1 Battery bank capacity required and system voltage selection

In fact, off grid solar power system must have battery bank that is capable to sustain the power required by the load within the time specified (autonomy) without interruption and while the voltage specification should be determined according to various factors and some of which are that the system may have DC load to supply to the specific DC voltage, or the inverter on choice requires the high DC input according to the high AC load output. Another factor that may require the solar system to operate on high DC voltage may due to the reduction of gauge of copper wire in between battery bank and solar array, so far the use of use of high DC voltage will totally affect in good way to make lesser the high current if the system were designed for low voltage such as 6V or 12V. That is the main reason behind for this project to select the high DC operating system voltage for all the equipment located in DC system. As previously mentioned, battery bank for any off grid solar power system is sized accord to the AC load, not the size of solar array, that why, when the sunlight is not available, the battery bank should keep supplying the load in systematic way.

4.8.2 Effect of temperature and depth of discharge of battery

The temperature effect on battery bank is another critical factor to take care when designing an off grid solar power system because of its role of storing electrical energy in form chemical means. That is the main reason to maintain battery system in the intermediate temperature to improve their functionality so that system battery bank can operate longer, here down is the table showing the effect of low and high temperature on battery bank system.

Low temperature	**High temperature**
Decrease the capacity of batteries	Increase the capacity of batteries
Raise batteries voltage	Lower batteries voltage
Increase the life span	Shorten the life span

Table 3: Effect of temperature on battery system

To design the size of the battery bank with accuracy, we will consider the battery temperature multiplier in the equation of calculating the total ampere hour required by solar system. Here in the table, let consider the room temperature of 60^{o}F or 15.6^{o}C that correspond to the 1.11 factor that will be used in the equation (6)

Temperature	**Battery temperature multiplier**
80^{O}F(26.7^{O}C)	1.00
70^{O}F(21.2^{O}C)	1.04
60^{O}F(15.6^{O}C)	1.11
50^{O}F(10^{O}C)	1.19
40^{O}F(4.4^{O}C)	1.30
30^{O}F(-1.1^{O}C)	1.40
20^{O}F(-6.77^{O}C)	1.59

Table 4: Temperature magnitude vs battery temperature multiplier

Another critical point to consider is the depth of discharge, it simply states how much energy is cycled into and out of battery with in the given cycle, however, this factor is expressed in percentage and the maximum value of DOD can't go below 50% for the lead acid battery, and battery bank is less discharged, it can increase the life span as fact that power it offered to the load is quite small and hence the autonomy is increased more than that is already calculated.

Let's size the battery bank required and see how much Ampere-hour required by battery bank.

$$\mathbf{Eb} = \frac{\mathbf{Et} \times \mathbf{DoT} \times \mathbf{T\ m}}{\mathbf{DOD}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (\mathbf{6})$$

$$\mathbf{Eb} = \left[\frac{\frac{\mathbf{10.543KWh}}{\mathbf{Day}} \times \mathbf{3days} \times \mathbf{1.11}}{\mathbf{0.50}}\right] = \mathbf{70.22KWh}$$

The energy of 70.22KWh is the total energy required by the load within the three days when the sunlight is not available, means, the solar modules are not receiving the solar radiation. However, the system voltage is 48V, and the battery bank or string would be wired so to meet the system voltage requirement of the entire solar power system. In the equation (7), the factor of 1000 is used to work on the common unit i.e, convert from kilowatt hour to watthour.

$$\mathbf{Amp_H} = \frac{\mathbf{Pm}}{\mathbf{Vs}} \times \mathbf{1000} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (\mathbf{7})$$

$$\mathbf{Amp_H} = \left[\frac{(\mathbf{70.22} \times \mathbf{1000})\mathbf{Wh}}{\mathbf{48V}}\right] = \mathbf{1,462.92Ah}$$

The total ampere hours of 1,462.92Ah are required within three days to run electrical appliance without interruption, however if the days of autonomy are completed while the sunlight is not available or weak and the battery bank has been used to 50% of the rated capacity, i.e the 4th day, the solar system will be out of service and there would be other means of charging to full capacity the battery bank either by using the diesel generator, but this is optional solution and will not be covered in this thesis development.

4.9 Battery bank configuration

The following step to consider is to work out how many number of batteries that will be connected in series and how many number of batteries that will be connected in parallel to comply with the system working voltage as well as matching them with other equipment of the entire solar power system.

By referring to the solar modules principle of configuration, the batteries will too be wired such that ones are series connected to increase the voltage to the specific operating voltage but keeping the ampere-hour unchanged while other batteries will be connected in parallel to increase the ampere-hour, but the system voltage unchanged. That is the main fact of making the string of batteries in series and others in parallel.

Let's for this project, selected the battery bank of the type of lead acid battery of the following specification: V= 24V, 380Ah.

4.9.1 Series battery's configuration

As already said, the connection of batteries will go from any terminal , let say positive of one battery to the negative of the second battery and the net terminal of the two batteries will be finally connected to the bus bar where negative and positive of the two batteries are separately connected. To the point of view of our case, let's work out the number of battery to be connected for series string and this will be determined by considering the system operating voltage and the voltage of single battery selected as shown by the following equation (8).

$$\mathbf{Nbs} = \frac{\mathbf{Vs}}{\mathbf{Vob}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots. (\mathbf{8})$$

$$\mathbf{Nbs} = \frac{\mathbf{Vs}}{\mathbf{Vob}} = \frac{\mathbf{48V}}{\mathbf{24V}} = \mathbf{2\ Batteries}$$

The two batteries will be wired in series and will respond to the system voltage of 48V with the total ampere-hour of 380Ah which is likely to mean that the voltage is added while keeping the ampere-hour unchanged to 380Ah as said above. Most of the manufactures recommend to do not make more than 4 series connections to avoid further loss. Here in the project, the two series battery are connected which is good as far as loss are concerned to be limited as low as possible.

4.9.3 Parallel battery's configuration

As previously discussed with solar modules, the battery bank also are connected in parallel to increase the ampere-hour by maintaining the voltage system constant and to fulfill that requirement, we will be using four strings of batteries connected in parallel by calculating the ampere-hour that each string would have. Here down is the equation that needs to be used to determine the ampere-hour per string required:

$$\mathbf{AmpH/String} = \frac{\mathbf{AmpH}}{\mathbf{4\ strings}} = \mathbf{Ah/String}(\mathbf{9})$$

$$\mathbf{AmpH/String} = \frac{\mathbf{1,462.92Ah}}{\mathbf{4\ strings}} = \mathbf{365.73Ah/String}$$

The choice of string depends on batteries capacity as well as total ampere-hour of the entire solar power system. Therefore, the total number of battery can be expressed by taking the number of strings in parallel times the number of battery in series as shown here down done.

$$\mathbf{Number\ of\ batteries} = \mathbf{4\ strings\ in\ parallel} \times \mathbf{2\ batteries\ in\ series} = \mathbf{8\ batteries}$$

4.9.3 Overall battery system's configuration

The overall battery system can be wired in series and in parallel, the purpose of doing so is to maintain the sustainability of power within the pre-determined period of supply. When batteries are connected in series increases the voltage and keep ampere-hour constant and when connected in parallel, the ampere-hour increases while the voltage remain constant. So that in this project, the both connection are used to maintain above characteristic to meet the requirement of the solar power system. Here down is the overview diagram of how the battery bank will be connected where we have 4 strings in parallel with only 2 batteries connected in series and provide the overall capacity of around 1,520Ah which is closer bit higher to the calculated Ampere hour of 1,462.93Ah and that is how practically it would be done and the current available corresponding energy of the battery bank can be evaluated by considering the chosen battery capacity of 380Ah as follows:

$$\mathbf{Ea} = (\mathbf{String\ Number} \times \mathbf{Amperehour})(\mathbf{Series\ Number} \times \mathbf{Battery\ voltage}) \dots\dots (\mathbf{10})$$

$$\mathbf{Ea} = (\mathbf{4} \times \mathbf{380Ah})(\mathbf{2} \times \mathbf{24V}) = \mathbf{72,960Wh}$$

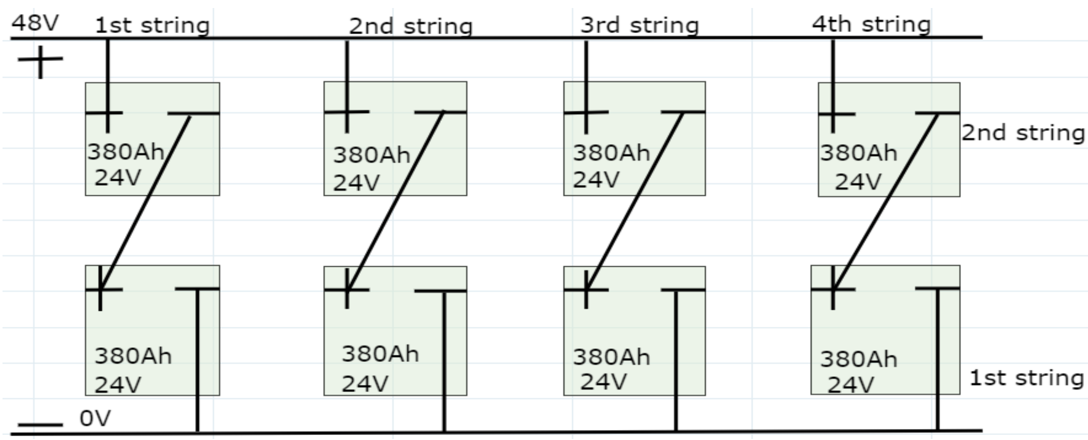

Figure 7: Overall battery system’s configuration

4.10 Size inverter for solar power system

Basically, an off grid solar power system should have an inverter that will have task of converting DC voltage from the battery bank to the AC voltage needed by the load. Most of today’s electrical equipment use AC power rather that DC power and that is why an inverter comes in to allow those electrical load to be connected. There are two type of inverters, the modified sine wave inverter and pure sine wave inverter, but the best here that matches with all electrical equipment is the pure sine wave inverter because it has the same shape of the trend as that of power of the grid and that why it is commonly used in off grid solar power system and is the best to use in the off grid solar power system than modified sine wave inverter.

In this thesis, it will be required to choose an inverter that is able handle the current load of Musenyi health center applied without effect of overloading but correspondingly to the calculated current load.

Generally, the inverter equipment should match the battery voltage picked (48V) and while the output power might be selected according to the load nature requirement. The output of an inverter can be three phase or single phase and so that before the use of it, there would be selection of which type of connection is required for the load. In fact, the inverter are designed to receive the DC voltage and convert to AC voltage with purpose of supplying the electrical load and it allows the flow of power from battery to load, but specific featuring, the inverter can have the way it charges the battery bank in the case the sunlight is not enough to charge the battery bank and this featuring help much more because if the grid is available can be used to support the solar array to charge the battery bank or the additional generator can be connected to it to do the same task as the power from the grid can do.

Inverter wattage and surge would be determined by adding the power of equipment and considering those with high power surging the solar system, so far, the inverter should be able to withstand the surge even more than 30% times to rated power and here down is the key elements to help choosing the right inverter.

4.10.1 Key requirement for choosing an inverter

There are several facts to consider while it comes to choose an inverter and some of them can be sorted out there:

Integrated AC charging: This is important feature to consider when AC power is available and can be used to charge the battery bank when sunlight is not sufficient.

Automatic generator start: Also very useful because can sense the status of the battery bank and decide to start generator when the sunlight is not sufficient to charge battery system.

Inverter transfer switch: Just as automatic generator start, the transfer switch can be incorporated in inverter to facilitate the accessibility of other external sources to charge battery bank for battery use and hold the efficiency reasonable.

Remote control and display: The remote control and display allows to track the performance of the inverter while it is far away from the solar system and that feature will not require to keep an eye on inverter all the time.

4.10.2 Size an inverter of an off grid solar power system

In fact, there is no off grid solar power system without an inverter, this a critical equipment that convert the DC voltage from the battery system to the AC voltage that is able to run AC electrical equipment, after the voltage has been converted, it is sent to the main AC power supply where there are too main AC protection according to the system requirement.

So far, to size an inverter requires to pay serious attention by evaluating the load that will run continuously and those that will run instantly and may cause the surge on the inverter. Normally, the surge is the high current drawn by the equipment at the starting condition and is quite high for the short period and the chosen inverter would respond to that surge by holding the solar system less affected. As we had previously calculated in the load profile record(fig 4), the overall power is 2,380W and from that data, we can now evaluate the minimum power rating of the inverter required to intermediate battery bank and the AC load by applying the following equation:

$$\mathbf{P} = \left(\mathbf{Pi} \times \frac{\mathbf{30}}{\mathbf{100}}\right) + \mathbf{Pi} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (\mathbf{11})$$

$$\mathbf{Pt} = \left[\left(\mathbf{2,380} \times \frac{\mathbf{30}}{\mathbf{100}}\right) + \mathbf{2,380}\right]\mathbf{W} = \mathbf{3084W}$$

The characteristic of inverter to choose on the market must respond to the following criteria of handling the surge of the connected equipment as well as the current load/power of (3084W) of the entire off grid solar power system. Here down is the minimum information of an inverter required in correspondence with the current load of the solar power system.

Electrical specification	**Rating**
AC Output voltage	400/230V
Max Output current	60A
Maximum power	3200W
Frequency	50Hz
DC Input voltage	48V
Output connection	Single/three phase

Table 5: Inverter electrical specification

4.11 Cable sizing and solar system protection

Electrical system are always subject to fault due to various factors which can be found in internal or external. The external fault are due to atmospheric condition behavior while the internal fault are due to the system overloading, heating or short circuit. The wrong the protection of solar power system leads to shortening the life of the equipment as well as the effect of causing complete failure and breakdown of the solar power system, in this thesis, I will be discussing the major way to protect various part of solar power system and work out the rating capacity required for the circuit breaker to protect the solar system. First of all, let’s go through the cable sizing and protection next.

4.11.1 Cable sizing from solar module to charge controller and to the battery bank

Previously, the capacity of solar power system has been worked out with mathematical approach to size the accurate solar system that matches with the load. The equipment be needed to be linked together to complete the off grid solar power system and there will be need of cable to through which electric charge should flow from solar module to the load. Ohm's law will be in use while considering at least 4% voltage drop of the rated voltage and taking consideration of copper resistivity of $1.72\times10^{-8}\Omega$m.

However, the Vpm is the maximum voltage that solar module can deliver at full load and can be seen on the electrical specification of the solar module, in fact, the module SD 250W selected has the overall maximum voltage at full load of 29.6V and are connected in series as well, hence the voltage will add up and be 59.2V while the Vd is the maximum voltage drop in the solar system and can be evaluated as follows:

$$\mathbf{Vd} = \frac{\mathbf{4}}{\mathbf{100}} \times \mathbf{Vmp} \ldots\ldots\ldots (\mathbf{12})$$

$$\mathbf{Vd} = \frac{\mathbf{4}}{\mathbf{100}} \times \mathbf{59.2V} = \mathbf{2.37V}$$

The minimum cross section can be evaluated by taking the minimum length to which the wiring must be made as well as the short circuit current that module can withstand under abnormal situation, in this case, the length estimated is 10m go and back with the short-circuit current of the four strings connected in parallel, however each module has 8.7A and are connected in parallel, the overall current will be added up or times 4 times the single current of the module which is actually 34.8A to be used in the equation 13 here down as overall short-circuit current:

$$\mathbf{A} = \frac{\boldsymbol{\rho} \times \mathbf{L} \times \mathbf{Isc}}{\mathbf{Vd}} \times \mathbf{2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (\mathbf{13})$$

$$\mathbf{A} = [\frac{\mathbf{1.72 \times 10^{-8} \times 10 \times 34.8}}{\mathbf{2.37}} \times 2]\boldsymbol{mm^2} = \mathbf{5.1mm^2}$$

The minimum cross section of $5.1mm^2$ is requires to link solar module to the charge controller and from charge controller to the battery bank.

4.11.2 Cable sizing from the battery bank to the input of the inverter

The cable size from battery bank to the inverter can too be worked out by considering the voltage drop on the side of battery bank to the inverter input (side of 48V system) as it is the same voltage to supply the input of inverter, however, the input of inverter find effective from 90% to 95% and let's use the overall efficiency of 92.5% in the following equation 14 to find the maximum current that is able to flow from the battery bank to the inverter as follows:

$$\mathbf{I} = \frac{\textbf{KVA of inverter}}{\textbf{Inverter efficiency } \times \textbf{ Rated DC Voltge of system}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (\mathbf{14})$$

$$\mathbf{I} = \left[\frac{\mathbf{3200W}}{\mathbf{0.925} \times \mathbf{48V}}\right] \boldsymbol{A} = \mathbf{72.1}\boldsymbol{A}$$

From the current above, it is now easier to evaluate the size of cable required by the inverter DC side and considering the voltage drop by applying equation (12) and the cable sizing equation (13).

$$\mathbf{Vd} = \frac{\mathbf{4} \times \mathbf{48V}}{\mathbf{100}} = \mathbf{1.92V}$$

$$\mathbf{A} = \left[\left(\frac{\mathbf{1.72} \times \mathbf{10^{-8}} \times \mathbf{8} \times \mathbf{72.1}}{\mathbf{1.92}}\right) \times \mathbf{2}\right] \mathbf{mm^2} = \mathbf{10.3mm^2}$$

From the above calculation, the minimum cross section of the cable required would be at least 10.3mm^2 with required length of 8m go and back from battery bank to the inverter input. Considering the variable in the equation (current and length requirement), the cross section can be higher or lower depending on the system loading. It is worthwhile to calculate according to the maximum loading to avoid future breakdown of system because of under sizing the cable and the associated equipment.

4.11.3 Cable sizing from output of inverter output to the distribution box

The sizing of the cable from output of the inverter to the distribution box should be determined with the following equation (15) if three phase output inverter is considered, however, there is advantages of wiring the output of the inverter in three phase, because the overall current is reduced 3 times as if the single phase inverter is consider and hence the overall cross section is reduced. The current in three phase system is determined by the following equation:

$$\mathbf{I = \frac{Inverter\ power(W)}{\sqrt{3} \times VL}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (\mathbf{15})$$

$$\mathbf{I = \frac{3200W}{\sqrt{3} \times 400V} = 4.61A}$$

Hence, using the equation 12, it is possible to determine the voltage drop per phase as follows:

$$\mathbf{Vd = \frac{4}{100} \times 230V = 9.2V}$$

Therefore, the cable cross section is determined by the equation 16, using the voltage drop and overall current already calculated previously by considering the estimated length of the cable of 100m.

$$\mathbf{A = \frac{\rho \times L \times I}{Vd} \times 4} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (\mathbf{16})$$

$$A = [\left(\frac{\mathbf{1.72 \times 10^{-8} \times 100 \times 4.61}}{\mathbf{9.2}}\right) \times \mathbf{4}]\boldsymbol{mm^2} = \mathbf{3.45}\boldsymbol{mm^2}$$

The minimum cross section of cable required to link the inverter to the distribution box is evaluated to 3.45mm^2, but the higher to that is highly recommended, say 6mm^2 is better that 3.45 mm^2 calculated. The rest of cable or conductor from distribution box to the other circuit can be evaluated according the power rating on the equipment.

4.11.4 Solar power system protection

In this solar power system, I will do sizing the breaker of various part of the system, the setting for the breaker will be 1.5 of the solar array, charge controller, battery bank and inverter. Let's go through them to get the approximate size of breaker that will be used.

1. **Protection between solar array and charge controller:** the size of the breaker will be little higher to the short-circuit current of each solar module. For the solar module selected, the short circuit current is 8.7A and that is the high current the module can offer. Following the solar module overview figure, the two modes are connected in series while the four are connected in parallel, so far ,it possible to determine the single modules protective breaker and overall protective breaker to maintain the flow the current from solar array to the charge controller and will be:

$$\mathbf{Ib1} = \mathbf{Ish} \times \mathbf{1.5} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (\mathbf{17})$$

$$\mathbf{Ib1} = (\mathbf{8.7A} \times \mathbf{1.5}) = \mathbf{13.05A\ just\ for\ single\ string\ \ module\ protection}$$

$$\mathbf{Ib2} = \mathbf{N} \times \mathbf{Ish} \times \mathbf{1.5} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (\mathbf{18})$$

$$\mathbf{Ib2} = (\mathbf{4} \times \mathbf{8.7A} \times \mathbf{1.5}) = \mathbf{52.2A}\ , \mathbf{just\ for\ string\ combined}$$

2. **Protection between charge controller and battery bank:** As previously calculated the overall current moving from charge controller the battery bank, that current will be used to size the breaker that is convenient to be placed between charge controller and battery bank. Here 1.5 factor needs to be times with the that current flowing in the charge controller or simply, the rating of the charge controller amperage can be used to size and mentions which breaker rating can be used.

$$\boldsymbol{Ic} = \mathbf{1.5} \times \mathbf{Ic} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (\mathbf{19})$$

$$\boldsymbol{Icb} = \mathbf{1.5} \times \mathbf{41.66A} = \mathbf{62.49A}$$

3. **Protection between battery bank to inverter :** In this way , to size the breaker between battery bank and the inverter will require to take account the battery voltage as well as the inverter wattage / power and the factor of 1.5 as previously considered, here down is the equation that comply with the size of the breaker.

$$\mathbf{I} = \frac{\mathbf{Rated\ wattage} \times \mathbf{1.5}}{\mathbf{Vs}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (\mathbf{20})$$

$$\mathbf{I} = \left[\frac{\mathbf{3,200W} \times \mathbf{1.5}}{\mathbf{48V}}\right] = \mathbf{100A}$$

4. **Protection between inverter and AC load:** This is the main breakers that will be required to protect the AC output of the inverter and the distribution box , the current drawing from the inverter to the load per phase will be considered to rate the breakers in the following equation:

$$\mathbf{I} = \frac{\mathbf{Inverter\ power}(\mathbf{W})}{\mathbf{Vph}} \times \mathbf{1.5} \ldots\ldots\ldots\ldots (\mathbf{21})$$

$$\mathbf{I} = \left[\frac{\mathbf{3,200}}{\mathbf{230}} \times \mathbf{1.5}\right] \boldsymbol{A} = \mathbf{20.87}\boldsymbol{A}$$

In the above equation, I considered the single phase line due to the fact that, the breaker protects the single pole of the line and is supposed to carry that current at full loading of the solar power system. Beyond to that current will lead to an overloading which leads to the thermal expansion of the conductors used, that why, it is very important to size the solar system according to the current loading capability and choose the correct cable or conductors fitting with the solar power system.

Additionally, the breaker to use here has the main task to interrupt the fault current under normal and abnormal condition with purpose of protecting the part affected without damaging the associated equipment. The fault is limited by opening the poles of the breaker and protect the portion between load and inverter , however, there are other protective devices that protect outgoing circuit in various places where electrical equipment are located surely known on main distribution box. This box has other rating breakers to protect various circuits.

5. **Solar surge arrestor, earthing and lightning protection:** this type of protection is adopted to protect solar off grid solar power system to maintain the safely of the system as well as the equipment connected to it, however, the solar power system is subjected on the dynamism of internal and external fault that may result the failure of the solar power system. The internal fault may due to the fault

of electrical equipment connected to it that finally intended to causes protective devices to react against by opening the poles to save the entire solar system, that why circuit breaker has been first introduced in various part of solar system. However, if electrical equipment has issue with the earth, there is high risk that person in contact to be affected by electric shock that severely can be the cause of the death. The earthing system works properly with the differential on the best to prevent that kind of electrocution by cutting off the supply of the selected circuit. The lightning protection is very essential for solar power system because are exposed much more on the lightning strike as solar system is made of electronic component that are risky to be damaged, therefore, it is strictly recommended to choose the size of lightning arrestor able to capture and divert that current due to surge to the earth to save the life of the solar power system. Musenyi health center should have the above protective means to be safe on operation and increase the availability of power without interruption.

5. Project price estimation and solar system configuration of health center

Solar power system is an attractive project for the investors to carry out rather that concentrating on other source of energy and that is because of it is easy to install, cheap compared to the grid and environmental pollution free compared to other sources of energy available. The cost of equipment will be displayed to show how much the project may cost and if needed to be implemented, the general idea will be found on various prices of the equipment involved.

5.1 Project equipment's billing estimation

This step consist of working out how much money will be spent on the project from the design to the implementation and commissioning. However, the solar power system is quite expensive at the stage of design and implementation while comparing to adoption of the use of the power of the grid, but the usability and reliability in operation and advantage it present qualify good drawback of the money invested in operation.

Type of equipment	Number	Rating/Capacity	Unit price	Total price
Solar modules	8	250W	$220	$1,760
Charge controller	1	60A	$300	$300
Bus bar	4	500A	$80	$240
Combiner box	4	N/A	$100	$400
Circuit breaker	12	15A, 20A,70A,100A	$22	$264
Batteries	8	380Ah	$250	$2,000
Inverter	1	3,200W	$650	$650
Cable	4	N/A	$250	$1,000
Earth system	1	N/A	$200	$200
Lightning arrestor	1	N/A	$55	$55
Surge arrestor	1	10KA	$200	$200
Accessories	20	N/A	$39	$780
Differential breaker	1	N/A	$120	$120
Positioning equipment	10	N/A	$72	$720
Measurement& Counter	1	N/A	$134	$134
Total	**NA**	**N/A**	**N/A**	**$8,823**

Table 6: Cost estimation of the project

The table above shows the cost of solar power system, it seems expensive at the start up because of equipment involved compared to the power of the grid, but if the system is well designed and the owner follows the routine maintenance and other safety procedure have the powerful impact to increase the overall efficiency and performance the solar system. In fact, the life span of solar power system is estimated to 25 years and above when the overall efficiency is kept above 80%.

5.2 The configuration of Musenyi health center off grid solar power system

The configuration of Musenyi health center solar power system intends to show out there the main part of solar power system as well as the main protection devices in every portion of the solar system. However, trading view is the application I used to facilitate in the drawing of circuit in this project and it is not easy to represent all the devices in the single diagram such as the on the part of distribution board, which would lead to complexity of the system and that is the reason of highlight only the main protection on DC voltage side and main protection on the AC side. The full operation is about to be discussed in details in the next section.

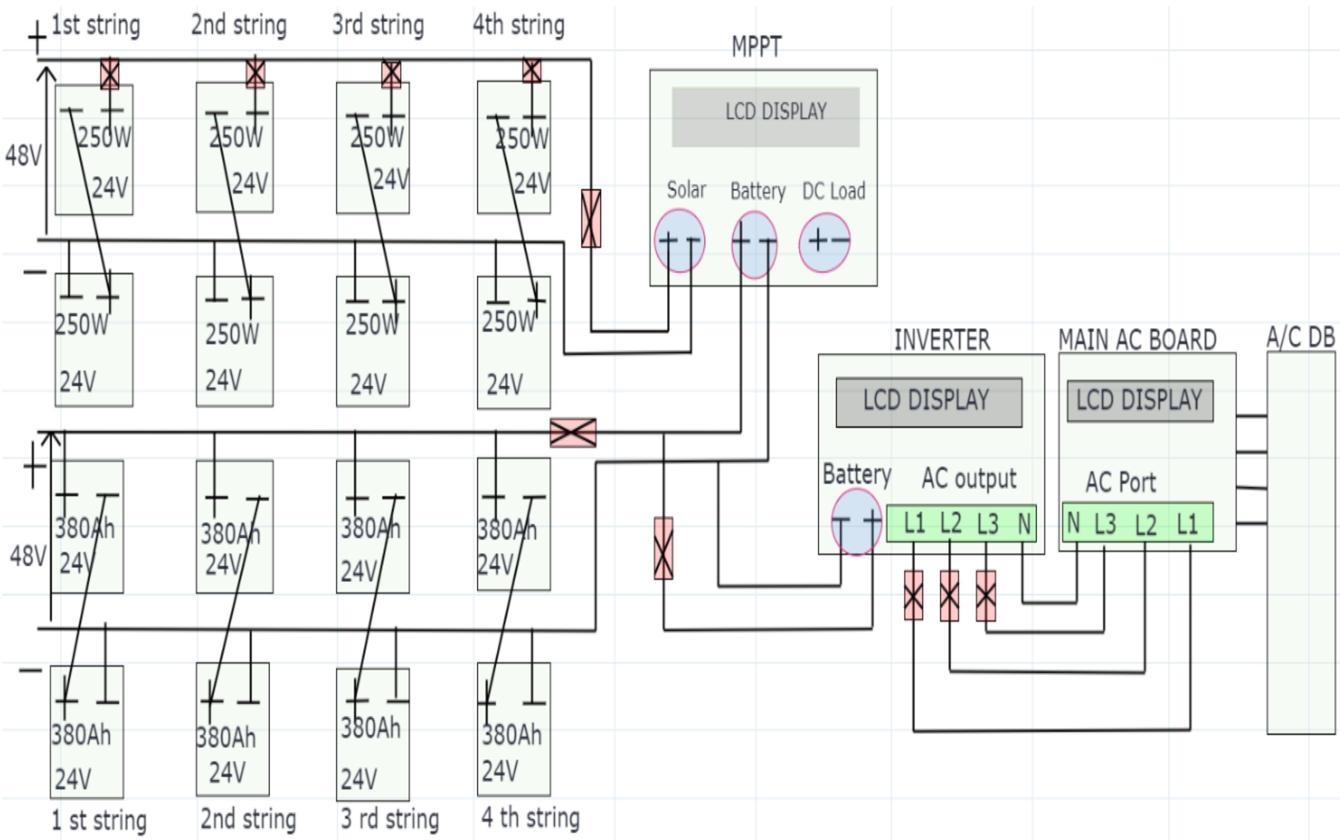

Figure 8: Complete off grid solar power system configuration

5.3 Discussion on the working principle of the sized off grid solar power system

As previously mentioned, the solar based generation is today performing in effective way, in various aspect of the life, but in this section I would like to express specifically how each part of solar power system will be working and introduce the basic operation of protective devices incorporate with the solar system.

In fact, the sun is the source of energy on the earth to which other kind of energies are derived, regarding the solar system, there are type of semiconductors that , when exposed on solar photo or radiation generated electricity. The process of allowing that semiconductors to behave so is known as doping which consist of adding the impurity in to change the behavior status, to which , when receive solar energy experiences the flow of electrons in junction PN, that flow is neither that electric current and solar module are operated on such principle.

However solar module is made up of cells connected in series to increase the voltage output as well as connected in parallel to increase the output current of the module. Specifically, the solar modules are connected in parallel and in series to fulfill the expected load requirement to which it will be connected and here in the design of Musenyi health center, the size of solar array calculated is around 2KW, under 48V system voltage as required by the equipment selected. In the design, the solar system array is made up 8 solar modules, each of 250W and delivering 24V. The solar system should satisfy preliminary load requirement characteristic where two panels are supposed to be connected in series to complete 48V and simply the system requires the 4 parallel strings made up of 2 modules in series.

Note that each string is protected by a single breaker to prevent short circuit and used carry out the maintenance on the need of the system and following the system modules configuration, the current flowing in the charge controller should be accurately known and safely supported by the charge controller without damage or harm. Charge controller between solar array and battery bank should allow the flow of charging current and breaker in between should reassure that fault located at that portion is cleared as soon as possible to avoid further breakdown or damage of the equipment.

The charge controller in the solar system will act as device that regulates the flow of electric charge to the battery bank as well as to prevent the flow back from battery bank to the solar modules array, there are many charge controller on the market, in this project, the maximum power point tracking (MPPT) is the best type of charge controller to stick on because of its overall performance in the solar system of maximizing the solar energy and maintain the constant charging current regardless to variation of solar radiation.

Another critical point to highlight here is the size of battery bank, it is the better to size it according to the need of the load, and batteries used in solar system are expensive and should be protected and use them accordingly, never discharge them too much to avoid shortening life span as quickly as possible. Here, in the designed solar system, each battery has the capacity storage of 380Ah under 24V, to fulfill the system voltage requirement as well as the days of autonomy desired, the battery system has 4 parallel strings made up of 2 batteries in series per string. The breaker is incorporated between battery bank and charge controller to limit the fault between them and well as to serve as isolating device for maintenance purpose when it will be needed.

The inverter is the main AC equipment that serves to convert the DC voltage to AC voltage due to the fact that most of today's equipment uses AC power. In the designed solar power system, there is breaker rated to protect fault between inverter and battery bank and can to serves as isolator for maintenance purpose. There too the protection provided between inverter and main AC board. Normally, this board has various protective devices and provides power to the AC distribution board which finally dispatch the power to the outgoing circuit where the equipment are placed. Finally, everything here complete each other, the protective breakers are sized according to the current flow in the circuit concerned and will react accordingly depending on the fault magnitude.

6. Conclusion, recommendation and future extension of solar power system

Rwanda government is currently facilitating more the stakeholders and shareholders to invest in energy sectors and that is because in the key development indicators, the energy possession count a lot as benchmark tools used to determine the economic growth of the country. However, Rwanda has multiple sources of energy such as that derived from water storage (dam), thermal (Diesel, peat or natural gas), power pool coming from neighboring countries and lastly solar energy, to which thesis has been thoroughly talking about. In fact, the solar power system is currently at low scale in terms of electricity generation compared to the other source of energy available in

Rwanda, and this is because of unfamiliarity of technology involved and the high cost involved when it comes to start a new solar power plant as it requires large space to set up the solar modules when it is needed to generated more megawatt (MW) and today, there is effort done about off grid solar power system and grid tied solar power system which denote the good progress and more similar project are yet to come in compound with other existing energy sources.

Currently, the installed capacity is about 226.4MW and intended to move to 554MW by 2020 and in the installed generation, only the demand required today is not above 150MW, while the 76.4MW remain unused (standby), there are many projects under construction that are awaited to boost the generation to the current level, but requires great effort and supervision so that they can be completed on time as seen that every year, the demand of energy consumption increases.

So far so good, the solar energy in Rwanda has become attractive project in some area of the country where the power of the grid is not yet extended and it is observed that off grid solar power system can offer the comfort of living once it is accurately sized according to the need of equipment in the house or area of living. The solar power system to which the thesis is carried out is based in Bugesera district, it is actually the place with reasonable sunlight than other regions of Rwanda.

In fact, Musenyi heath center had an old off grid solar power that were not effective at all due to various factors previously enumerated in this thesis that were the major key factors of breaking down the existing off grid solar power system and so that, it was proposed to design and size again the new solar power system according the current demand or load profile of the Musenyi health center. The important steps in design and size the off grid solar power system have been followed to avoid further premature failure where the step one were to determine the load profile to be supplied by the solar power system, and this is the main point to which the choice of solar modules, charge controller, battery bank and inverter are based on and so that under sizing is the reason that conduct to the failure in the future.

In the recommendation, I would like to advice on how off grid solar power system of Musenyi would be operated and maintained as it is an important key of holding the system performance and effectiveness. Specifically, the system is supposed to operate within three days without the sunlight once the battery bank is fully charged and that why autonomy comes in while design solar power system that is not depending on the grid or other sources of energy. The existing generator can be used for other purpose or other way used to charge battery bank when required, but this is optional idea and was not included in this final thesis, but is possible to be done. To maximize the efficiency of solar power system, it is highly required to do not discharge the battery bank below 50% if so, the life of battery bank will be reduce, normally, if battery bank is used in good condition can last longer to 15ans. So that periodic maintenance should be carried out to avoid premature failure on quarterly basis. The maintenance should be also be done on the side of solar array system to remove the dust, debris and heavy particle that may have preventing the outer surface to let solar radiation to be absorbed by the silicon devices inside the cells of the module for electricity generation and additionally to this, the entire solar power system should be free from shading object, the shading effect may due to the any object that prevent solar module to maximize the sunlight which affects much more the generation of electricity from the photovoltaic array as well and should be avoided for better performance. Any fault in solar power system should be investigated and analyzed with purpose of taking preventive action for future similar case.

Lastly, the off grid solar power system can be used to anyone of who needs to be independently satisfied on power generation. In fact, the thesis development was dealing with the right way of sizing off grid solar power system based on load profile and the similar way can be followed to design and size any other off gird solar power system depending on the load profile available. In fact, when there is a need to apply any other additional load to the existing load, a care should be taken to avoid any further issue of exceeding the loading capability which may cause breakdown of the entire solar system. However, it is highly recommended to consult an electrical engineer or contractor of solar system for the support to assess the impact of the new load and provide feedback to reveal where it is necessary to increase number of modules or not, number of batteries in the battery bank system, charge controller or not. Note that, the bigger the load to apply, the high the chance of tending to return on the design and size of solar system, which would be better solution than overloading the existing solar system and design it according the current load. On other hand, the current Musenyi health center can be tied with the grid when transmission line will be extended to the area and the power it generates, can be intermittently used by itself and the excess send back to the grid to get paid back according to the power generation, and is the reliable solution that can be worked in the future desire on this project which may involve the additional equipment and change in configuration.

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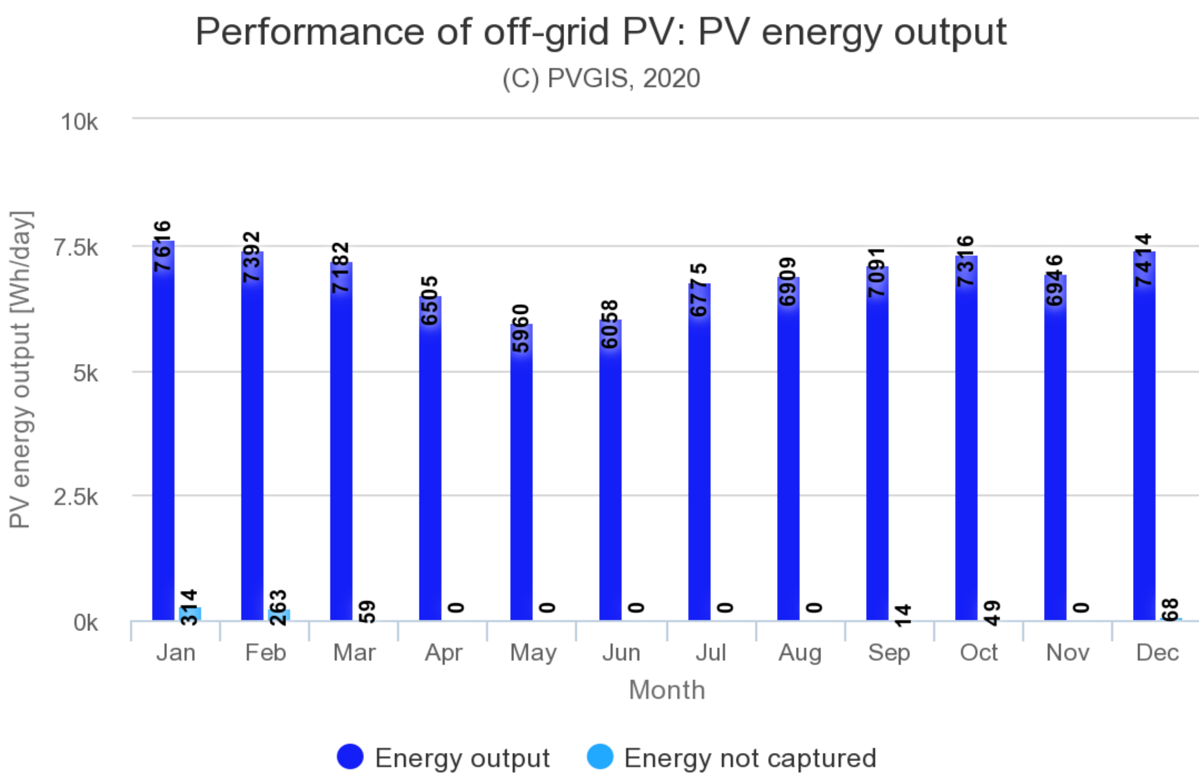
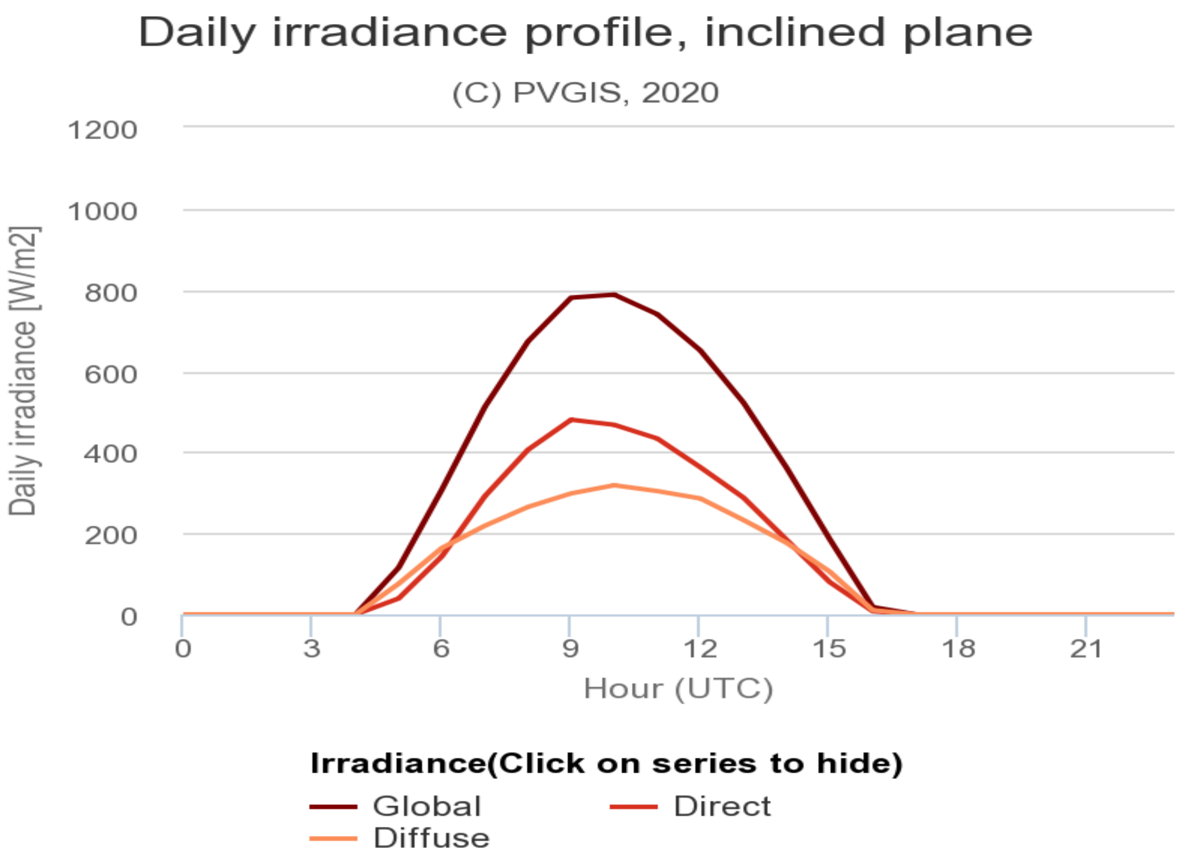
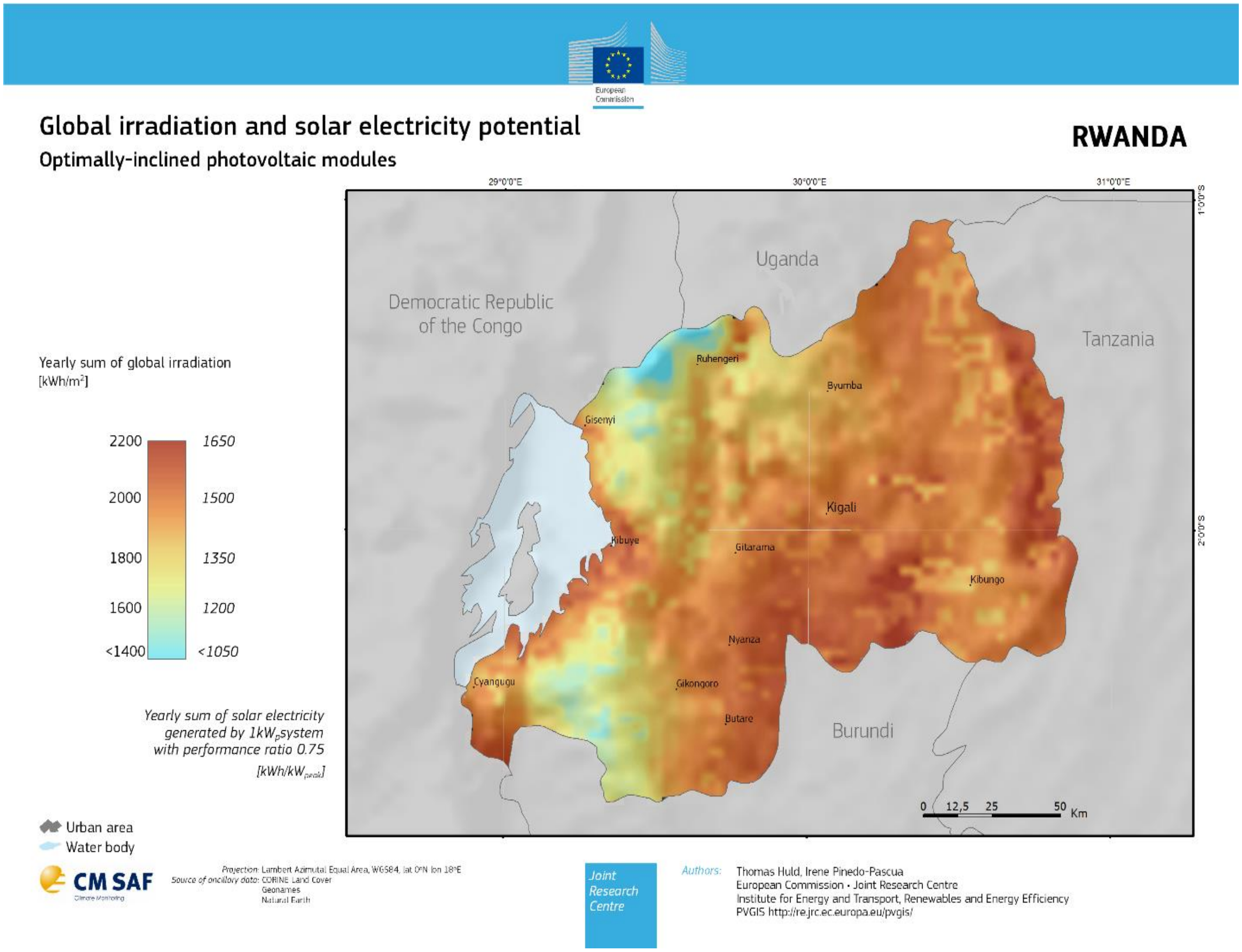
Appendices



Appendix A: Performance of solar array on monthly basis of Musenyi health center



Appendix B: Daily solar irradiance of Bugesera district specifically the region where Musenyi health center is located



Appendix C: Global irradiation and solar electricity potential in Rwanda

ELECTRICAL CHARACTERISTICS AT STANDARD TEST CONDITIONS (STC)*	235Wp	240Wp	245Wp	250Wp	255Wp
Power Tolerance	+/- 3%	+/- 3%	+/- 3%	+/- 3%	+/- 3%
Min Power (W)	228	238	243	248	253
Voltage at Max Power (Vmp)	29.40	29.00	29.20	29.60	30.00
Current at Max Power (Imp)	8.04	7.90	8.10	8.20	8.40
Open circuit Voltage (Voc)	36.90	36.00	36.20	37.00	37.20
Short Circuit Voltage (Isc)	8.65	8.00	8.40	8.70	8.90
Maximum System Voltage	1000	1000	1000	1000	1000

Voltage temperature correction factor (Open Circuit)	-0,35%/°C
Current Temperature correction factor (Short Circuit)	0,05%/°C
Power Temperature correction Factor	-0,44%/°C
NOCT	45°C +/-2°C
(STC) Standard testing conditions :	1000 W/m², AM 1.5, 25°C
Safety Class	Class II
Max. Over-current protection rating	20

Appendix D: Electrical specifications of solar module SD 250W selected

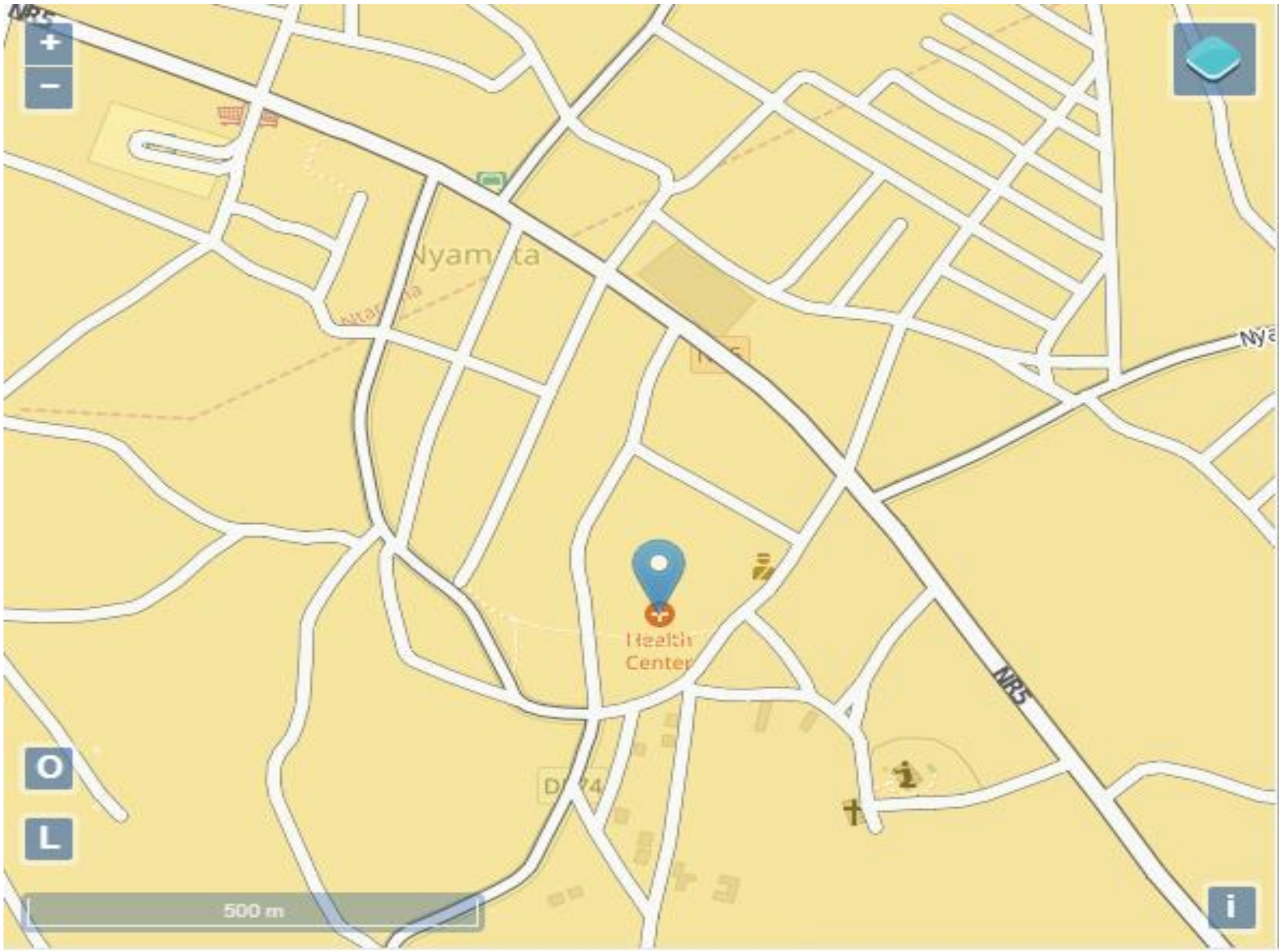
SDDirectPro

MODULE SD250 POWER

MECHANICAL CHARACTERISTICS	
Length	1660mm
Width	990mm
Height	45mm
Weight	19Kg
Junction box	1 x Tyco junction box with 3 Bypass diodes
Cables	Solar Cable, Length 1000mm, 4mm² thick Assembled
Front Substrate	HiT SM, ARC White Glass 3.2mm thickness
Cells	60 Polycrystalline Cells (156 x 156mm)
Encapsulation	EVA - Ethylene Vinyl Acetate
Back Substrate	Composite Sheet Tedlar or APA
Frame	45mm Aluminium profile - Natural or Black Anodized
Unframed dimensions	1652 x 982 x 5mm (LxWxH) (Tol. +/- 2mm)

CERT TÜV PV CYCLE CE

Appendix E: Mechanical specifications of solar module SD 250W selected



Appendix F: Musenyi health center village located in Bugesera district, Eastern province of Rwanda