Title: Assessment of solar radiation intermittency on grid-connected PV with storage system

Thesis number: ACE-ESD/PSE/20/03

Student names: Patrick Ndayisenga

Registration number: 215025993

A dissertation submitted to the African Center of Excellence in Energy for Sustainable Development

College of Science and Technology,

University of Rwanda, in partial fulfillment of the requirements for the degree of

MASTERS OF ELECTRICAL POWER SYSTEM

Supervisor's names: Dr. Charles Kabiri

October, 2020

Declaration

I, the undersigned, declare that this project proposal is my original work, and has not been presented for a degree in University of Rwanda or any other universities. All sources of materials that will be used for the thesis work will have been fully acknowledged.

<u>Names</u>: Patrick Ndayisenga __________

Signature

Date of Submission: ______

This thesis has been submitted for examination with my approval as a university advisor.

Digitally signed by
Kabiri Charles
Date: 2022.05.20
03:28:47 +02'00'

Supervisor: Dr. Charles Kabiri ___________ _____

Signature

Abstract - Grid-tied distributed photovoltaic system has brought a significant use energy generated from solar, but it has proven to have a serious impact on the load characteristics in terms of quality, line losses, and power instability of networks it is connected on due to its unreliability and volatility. The penetration of large-scale photovoltaic (LSPV) energy into an existing power grid is expected to highly increase which leads to a significant effect on the grid operation. Solar Photovoltaic (PV) systems are having growing importance in the present time of our power system due to its non-polluting, minimum maintenance, and free fuel characteristics. This research analyzes the effect of solar radiation intermittence on solar photovoltaic generation. Also, a long-term solar radiation intermittent mitigation solution has been provided by proper assessment of solar behavior which led to a proper sizing of energy storage systems. The solar radiation prediction results were the prime consideration to size a storage system for an 8.5 MW case study. The storage system was a lithium-based technology due to its different advantages compared to the acid-based batteries.

Key words: Grid connected, PV system generation, battery sizing, energy storage, Lithium-Ion battery.

List of figures

List of tables

List of abbreviations

PV: Photovoltaic

AC: Alternating Current

DC: Direct current

LS: Large Scale

RESs: Renewable Energy Sources

PDGPY: Power of Distributed Generation PV

PPYH: Power of PV per hour

BESS: Battery Energy Storage System

SOC: State of Charge

CCM: Coulomb Counting Method

LCO: Lithium-Cobalt-Oxide

LMO: Lithium- Manganese-Oxide

NCA: Nickel-Cobalt-Aluminum

NMC: Nickel-Manganese-Cobalt

LFP: Lithium-Iron-Phosphate

LTO: Lithium-Titanite-Oxide

1 Introduction

1.2 Background

As there is a fast decrease in conventional energy generation sources, the world is moving forward to an electrical power decrease at a fast rate. Furthermore, the normal energy generation resources have a reverse relationship in terms of availability and cost-effectiveness, and they are not environmentally friendly. Due to this electrical power scavenging from renewable , energy from solar, geothermal wind, etc., are becoming the mostly exploited nowadays [1]. The increase use of energy from solar radiation introduces has brought more technical drawbacks due to the unreliability supply of this source, which is influenced by nature and meteorological constraints, as well as other factors. Due to this unpredictability and the unreliability of solar energy, any grid-tied solar photovoltaic plant is said to be an unmanageable in terms of control and non-dispatchable energy source with variation in its power output that brings problems to the power stability to the existing electrical network [2]. The electricity generated from the solar energy has its drawbacks as the sun reaching on the earth's surface depends on the strength and the angle at which solar rays are tilt on which changes due to differences in latitude and position of the sun. Changes related to the seasons and cloud coverage have a significant impact on how much sunlight the available on the earth's surface. The effect brought by cloud cover has a Significant impact on the output of solar PV plants which has the ability to cause variable power output which results in demand forecasting and maintaining power stability is difficult [3]. The high uncertainty of the availability of the solar energy source makes the operation of the microinverter difficult with only one single input unit. Hence, there is no doubt that continuation of providing power to meet the needs of consumers at all times will continue to be absolutely essential. Therefore, energy storage may be one of the important ways to solve the fluctuation of renewable sources because storage services can smooth out the power output of Renewable Energy Sources (RESs) by configuring a certain capacity. However, these storage services require a suitable control strategy [4][2]. Integration of energy storage system in the solar PV requires knowledge on the solar radiation behavior for a particular place. There some factor to be considered when assessing the solar radiation are environmental factor that we have no control over them. Number of the PV radiation issues are due to variation of solar radiation which is predictable cause, and the cloud cover which is unpredictable causes. These two important causes lead the PV to generate less energy than what it could have been generated if is working at its Maximum Power Point

(MPP). At this time, the power supplied into a grid is less than what utility was expected, and voltage will dip during this period [5], [6].

1.3 Problem statement

Due to the inconsistency of the weather conditions all over the world, continuous solar energy conversion is not possible which results in significant variation of the solar plants output voltage. This voltage fluctuation leads to the grid power instability as well as line losses, hence, disconnected from the grid. However, unreliability and unpredictability caused by the prominent sources of renewable energy, such as wind and solar are giving a headache to the normal operating power generations. This intermittent can be addressed by studying properly the solar radiation behavior then later integrating energy storage into the system. This will help global energy conversion to mitigate voltage fluctuation that in turn stabilizes electrical power networks. The real fact is that the efficiency of solar energy conversion is 20% which is still a small scale to be enough to support the grid voltage fluctuation. Its exploitation should be done at its maximum to optimize voltage they are generating. Since most of the grid-connected doesn't have energy storage, they are not enabled to stay connected to the grid when there is no enough radiation to generate the voltage within permissible limits. For this fact, a big number of grid-tied PVs are being isolated from the grid when the voltage falls below limits.

1.4. Objective

1.4.1 Main objective

Based on the current situation where most photovoltaic generations are not able to stay connected on the grid because of the solar irradiation is not predictable and intermittent. The generation pattern does not match the load pattern thereby creating a need for a long-term solution for mitigating power unreliability. There are quite different models to be involved during solar irradiation estimation. Among them, there is β probability function and Meteorological Radiation Model (MRM) that will be right tools to use in this study to predict solar irradiation. Having accurate information about solar radiation variation and intensity, a long-term mitigation will be sizing the battery storage system to back up the system during the night or when the solar irradiation is pretty much zero. Because the financial costs needed for energy storage are significantly and grid- scale storage technologies are still adequate, it is important to determine the amount of energy storage that can be integrated with the grid to solve the availability of supplies intermittent. In this research, we are aiming to estimate randomness of solar radiation using Meteorological Radiation Model (MRM) then later from the results, we will be able to size a battery storage system for a case study (Rwamagana) PV that will help the plant to optimize power supply to the grid just in case the weather condition are not friendly for the plant to generate power to stay connected to the grid.

1.4.2 Specific objectives

In this study, a recent solar radiation data request from Rwanda Meteo (2018 - 2020). The data will include daily global solar radiation in Eastern province stations very specifically to Rwamagana. Use of solar data from my reference paper ranging from 1999-2019 taken at Kanombe station will be added for better accuracy as will having a big sample. PV related data will be requested from GW Rwamagana PV plant but this will be an online request rather than site visit. From the data requested, assessment of solar radiation behavior will be carried out later alone providing a long-term solution for solar radiation intermittent by properly assessing solar radiation behaviors on a time basis. The analysis will be done by evaluating, plotting and interpreting the collected data using google sheet. Having the accurate information about weather variations, this will be a required input for a case study to size a storage system that will take over the load to optimize power supply just in case solar radiation fall beyond the required amount for the plant to supply enough power to the grid at which it is tied on. The storage system design will be made by a battery bank with a certain number of batteries among them, the number of parallel batteries will be calculated to meet the battery bank current as well as calculating the number of batteries that make a Serie string. Finally, a relevant conclusions and recommendations related to the contribution of the study in the society will be drawn.

1.5 Scope of study

The study will be started by better understanding theories and facts related to solar photovoltaic plants for both grid-tied and standalone, understanding the effect of weather conditions and sunlight irradiation on the operation of PV plants, understanding different extinction phenomena of solar radiation such reflection, absorption, scattering and diffusion that most of the time affect the solar plants operations. A deep study to understand the solar radiation variation within a specific time and specific area where a case study is located will be a prime mover of this study. All the theories will be followed by an optimal Sizing PV storage system which is cost-effective, reliable, and simple for operation where Lithium -Ion batteries will be the right battery component to build storage features. In this research, we will not design a new PV, but we will consider one case study of the existing PV plant parameters and integrate new features (storage system).

1.6 Expected outcomes and significance of the research

1.6.1 Expected outcomes of the study

To provide a long-term solution for grid -tied solar photovoltaic generation by providing an estimated solar radiation then properly size a cost-effective battery storage system to address the problem of solar radiation intermittency.

1.6.2 Significance of the study

After this research, we will be aware of the Rwanda solar radiation variation then will be able to predict PV generations. Optimal Sizing of PV storage systems will be a long-term solution for solar irradiation unpredictability Mitigation hence continuous power supply. To deal with the unreliability of the solar PV source of power, a number of models are involved including probability density function and Meteorological radiation Model. From solar radiation awareness, a battery energy storage system where Lithium Iron cells will be the best component of our battery feature. The battery storage system will be sized at optimum to meet the state of charge limitations. A case study will be to explore the possibility to size Rwamagana PV storage to back up this plant in case there is a significant dip in voltage due to low sun radiation.

1.7 Motivation of the study

A big number of the Rwandan citizens lives in remote areas where their daily lives rely on firewood as their basic energy source. Currently, the government of Rwanda is investing more in renewable energy, especially solar photovoltaic systems to help people who live in places where they are not able to access the electricity of grid. As the country develops in economic terms, the investors are willing to invest in this area and develop commercial PV generation that is tied to the network grid. Rwamagana PV is the first and large grid-attached plant and its power supply is not due to intermittent solar radiation. To overcome this problem. a better prediction of solar irradiation should be in place. To do so a deep study about solar irradiation is needed. This research aimed to provide a reliable and cost-effective solution in the worst-case scenario of power stability and economic dispatch for existing and upcoming projects of solar energy related projects.

2 Literature review

2.1 Background

In[7], As a results of the abundance of solar energy from the sun, solar photovoltaic (PV) generation has undergone tremendous growth in the world as renewable energy generation. Major research in the field of solar power as a means of producing electricity has resulted in the need for renewable, a new form of energy mix, and a reduction in carbon emissions. The energy growth and demand are projected to increase by approximately 41% worldwide by 2035 and this has led to a vested interest in solar system generation research and investments and their and incorporation into the grid affect the current grids. The incorporation of the PV into an existing investment in the field of solar system generation and their integration into network affects an existing grid has a good number of consequences. In the most part of the world the substantial rise in solar generation is attributed ample availability of solar, the conversion to electrical energy a priority in both developed and developing countries [3], [8]

2.2 Stand-alone photovoltaic generation

The system which uses the only energy from solar electrical power as the primary source of power is known as a stand-alone solar electrical generation. There are many places on this earth where no conventional source of energy is available. At these places, the standalone solar power ways can be the ideally used as source of electrical power [1], [2]. The main advantage of this generation means is that it doesn't need to be connected to the main grid, it is independent source of electricity. These types of generation can generate energy to the local DC loads or use other ways to change the DC into AC to supply local load center that use ac power [4]

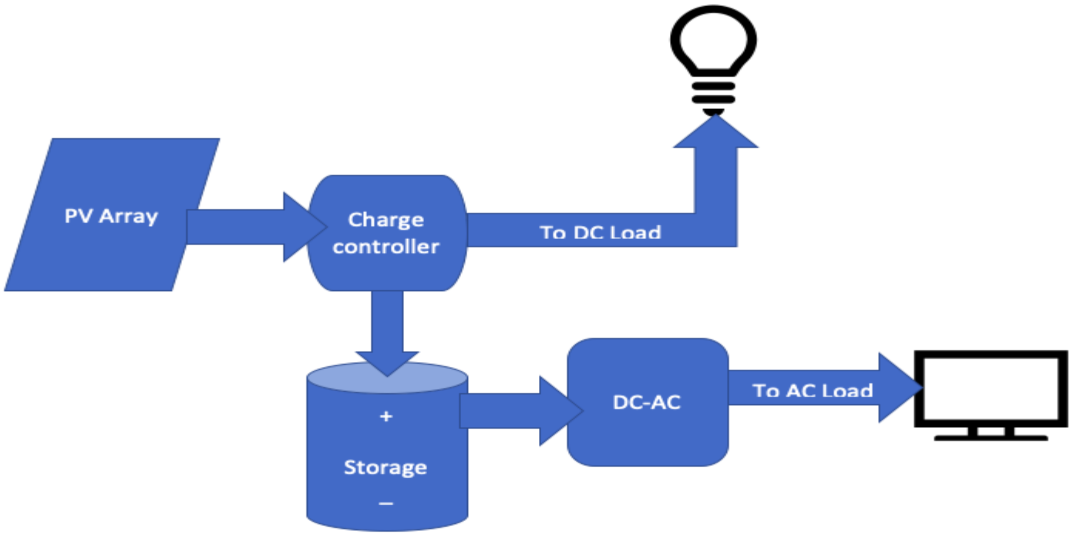

Figure 1: Stand-alone PV

The figure 1 shows a typical standalone solar photovoltaic plant. It consists of a PV arrays that generate a DC power that need to be converted in different forms depending on the load that need to be supplied. The output of the PV array is fed to a charger controller to regulate the charging process by limiting the voltage that will be stored by battery bank. The output of charge controller cane be fed either to the storage or directly to the DC load. To supply the AC at the load center, the energy will be converted into AC. In [3] The PV generation system can be connected to a grid or can be used in stand-alone systems; in the military and distant relief and other emergence situations the stand-alone PV generation can be widely used. Many remote areas, no man equipment, islands, and vehicles need uninterruptable PV systems to supply electricity. Depending on the climatic conditions, the maximum power of the PV arrays can be generated. The maximum power point monitoring MPPT is normally enforced by the DC-DC converter between the PV panel array and the battery to collect the maximum of the PV panel array. A step-up inverter is needed to supply an AC load with the alternative power. In view of the fact that a DC-DC converter often have all the power produced in the Serie connection, a number of conversions reduce the overall performance. The parallel connection of the MPPT circuit was integrated as an alternative to this configuration. An example of Serie relation is shown in the figure below.

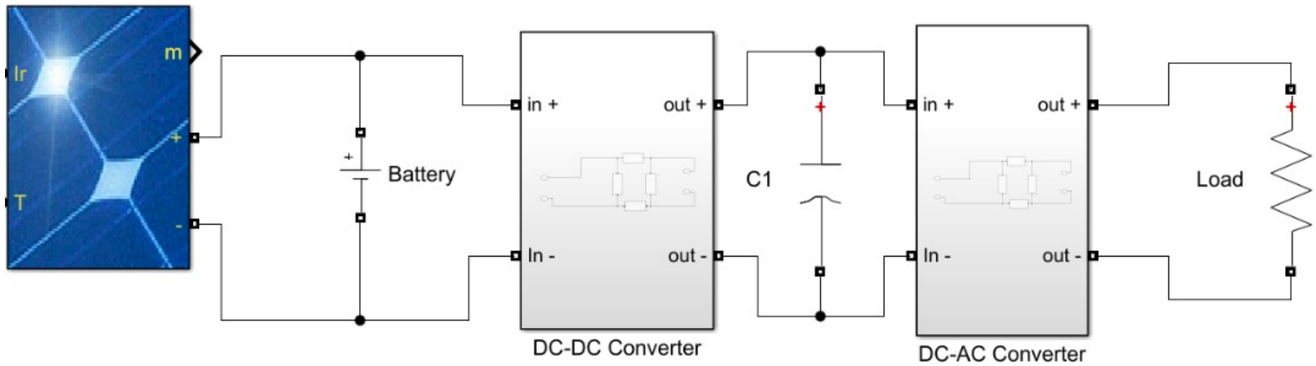

Figure 2: Stand-alone serie connection

2.3 Characteristics of PV generation

In particular, concentrated solar power CSP and solar photovoltaic PV have advanced solar generation technologies in two different ways. The CSP technology uses thermal energy that is reflected by a focal receiver that focuses on thermal energy. This concentrated thermal energy is used to heat a fluid that expands and is then used to drive an alternator – shafted turbine. The alternator is then used for electrical energy generation. The working theory of CSP plats show the same behavior as the regular generation of electricity. On the other hand, solar PV generation, by contrast converts solar energy from the sun either in the form of radiation or thermal energy into direct current D.C electricity [4]**.** The last is the mostly used in normal generation of a big amount power then later tie it into the existing grid.

2.4 Grid connected photovoltaic generation

The complete block diagram of the grid-connected photovoltaic system, shown in Figure 3 consists of photovoltaic (PV) panels that produce electricity from solar radiation to satisfy the demand for electrical load, a DC/DC converter so that the DC output voltage can be balanced and increased or decreased. An inverter that transform a direct current (D.C) into alternative current (A.C) and utility grid that intends to supply electricity to the system where there is no production (at night and cloudy days) [5].

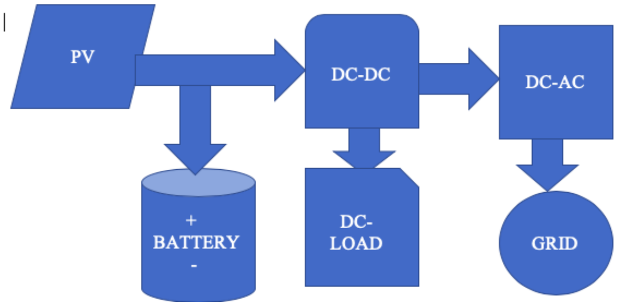

Figure 3: A complete grid connected PV generation

2.5 PV transient stability constraint on grid

In [1], integration of a large scale (LS) photovoltaic (PV) system into a running power grid has brought a more negative effect on voltage regulations, energy quality (increase in voltage, frequency variation), operating behaviors and grid misbehaving. The power system stability is said to occur when the power network has a capacity to return in its normal state without losing synchronism to a steady-state. The stability of the power system is classified into constant state stability and dynamic state stability. Several measures have put in place to sort out the problem that is being brought by the fact of integrating the PV into the existing grid. The last among the three is more affected by PV [4], [5].

2.6 Solar photovoltaic generation

Solar photovoltaic energy generation is a variable over time and it is a probability function of solar radiance. The solar generation is not consistent over time that why the generation capacity and reliability require a proper prediction in terms of solar radiation behaviors so that operator can keep play with those changes related to the sunshine. To do so we need a proper awareness on solar radiation variability on time basis.

2.6.1 Mathematical model of solar radiation

In terms of distribution function, radiation data are interpreted in two separate ways for a given time (hours and days) of each season. The data of solar radiation was divided into two classes with a function of unimodal distribution. Therefore, a Beta probability function is used for each unimodal to display its unreliability phenomenon of solar radiance data. This solar radiance randomness behavior can be expressed via a function of Beta probability density [6].

$$B(\alpha,\beta) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} S^{(\alpha-1)}(1-S)^{(\beta-1)} \quad (1)$$

$$0 \leq s \leq 1 \quad \alpha,\beta \geq 0$$

$$B = (1-\mu)\left(\frac{\mu(1-\mu)}{\sigma^2} - 1\right) \quad (2)$$

$$\alpha = \frac{(\mu\beta)}{(1-\beta)} \quad (3)$$

where Γ: gamma function

S: Solar radiation random variable in $KWh/m^2/day$

$fp(s)$: Function of Beta probability density of s

α,β: Beta distribution parameter

μ,σ: mean and standard deviation

2.6.2 Numerical calculations of PV module output

The output power of the PV module depends on the solar radiation and the ambient temperature of the location and its module characteristics. Therefore once the Beta probability function is calculated for a given segment of time, the output power at various condition is calculated using the following mathematical equations for this time segment [9][10].

$$T_{cy} = T_a + S_{ay}\left(\frac{N_oT-20}{0.8}\right) \quad (4)$$

$$I_y = S_{ay}[I_{SC} + K_i(T_c - 25)] \quad (5)$$

$$V_y = V_{oc} + K_v T_{cy} \quad (6)$$

$$P_{sy}(S_{ay}) = N\ FF\ V_y\ I_y \quad (7)$$

$$FF = \frac{V_{MPP} I_{MPP}}{V_{oc} I_{oc}} \quad (8)$$

S_{ay}: Average solar radiation at state y [6], [7]

T_{cy} : cell temperature °C during state

T_a : Ambient temperature °C

K_v : voltage temperature coefficient V/°C

K_i : Current temperature coefficient A/ °C

N_oT: Nominal operating temperature of the cell in °C

V_{MPP}: Voltage at maximum power point in V

P_{sy}: Output power of PV module during state y

I_{MPP}: Current at maximum power point in A

I_{oc} : Short circuit current in A

V_{oc}: Open circuit voltage in V

FF: Fill factor

2.7 Energy constraints in Rwanda

There are different energy sources in the world, among them being available in Rwanda but due different economical and their initial constraints, they are not exploited at their maximum. The energy generated from wind in Rwanda is very limited. Diesel energy is very closetful as it being bought from outside of country. The use of methane gas to generate energy is not environmentally friendly due to its CO_2 emission mainly due to the composition of the crude gases extracted from the lake. Nuclear raw materials are more political due to different important manufacturing concern. From all different raisons, the solar energy has been adapted and recommended [8]. That is why a research is needed to address this in order to have accurate information for better understanding the behavior of solar radiation on monthly basis over Rwanda. Since Rwanda is small country with 26338 km^2 characterized by a mountainous topography where by a climate is keep changing over time, hence a proper prediction and estimation are being done by various researcher.[5], [6].

2.7.1 Global solar radiation over Rwanda

Prediction of solar radiation data is an important consideration when modeling solar radiation systems [11]. Most of the countries located in tropical regions are characterized by less investment transmission and distribution lines infrastructures. All countries in these regions have to find other means to get electrical energy. Solar has been adapted to be a possible alternative than conventional energy sources even though it seems to be having a high initial cost. Regions located in the tropical belt are receiving abundant overhead sunshine that is why there will always be a great need to estimate the amount of solar radiation over there and its variability as well. Rwanda is in need of having accurate information about solar radiation behaviors since most of the Rwandan are living in remote areas where access to the electrical network grid is still a big challenge, therefore they will be a need to use Solar as their prime source of energy. There are different reasons for these regions to have fewer electrical infrastructures over there such as land complications and well as per capita income of the country. Having accurate information on solar radiation will help in the design and size of the solar system of all solar-related systems to meet the demand requirements and other climatic related researches. By considering Rwanda as a particular case, there are a big number of factors that influence solar radiation availability such as geographical constraints where cloud covers are prime consideration as a key factor in the radiation change as well as solar radiation clearness index. Astronomical and diffuse characteristics also play a significant role in solar radiation variability. Besides, daily and seasonal variability make a big impact on solar radiation behavior that in turn leads to solar radiation intermittent. Rwanda is considered as a particular case where the access to electricity is still less than 5% of the population, the solar sources are enough but there is insufficient and relevant information about solar radiation behavior on a monthly basis to address that issues. Any process in the development energy sector over Rwanda can be optimal when promoting energy generation by considering the increase of existing and progress done in PV devices and materials from the advanced countries [8], [9].

2.7.2 Contribution of radiation data in PV sizing

As per the above information, the aim of this research is primarily contributing to the skills and information related to solar energy resources over Rwanda. As an illustrative application, any electrical related solar activities and projects require a prediction of several important aspects and parameters that involve optimizing and sizing of solar systems like number of PV modules (N_o) as per energy demand (E_d) . The mentioned parameters depend on the global solar radiation (G_n) received by a particular place where a PV plant is preferred to be settled. All these parameters (G_n) , (N_o), and (E_d) can be related each other as follows. [11][12].

$$N_o = \frac{\Gamma E_d}{G_n} \quad (9)$$

where Γ is a factor related to the efficiency and the performance of the PV plant components[11].

In the happy sky conditions, (G_n) is linked to the daily extraterrestrial radiation (E_d) and atmospheric conditions in real time.

2.8 Losses in distributed PV

This research deals with the optimum dimensioning of the combination of solar PV batteries in a grid connected system. Solar PV generation is seen as the source of the future generation and with its mature technology, battery storage will help it become reliable source in power system[10]. From paper [6], Because of the high level of unpredictability and intermittent associated with them, energy supplies from prominent renewable sources such as wind and solar are limited. This contribute to these sources getting an inefficient and less consistent performance. Therefore, while placing them on the feeder, proper generation prediction, sizing, and intermittent mitigation of renewable energy source (RESs) such as wind and solar photovoltaic (PV) are necessary. As these sources are distributed energy sources, in addition to their generation support, loss minimization may be one of the possibilities. In paper [7], energy storage can be one of the key ways to overcome the fluctuation of the renewable energies, since by configuring a certain capability, storage services may smooth but the power production of renewable energy sources (RESs). These storage facilities, however, includes an acceptable energy loss management strategy. In the scientific literature, numerous control methods are proposed, several of which use short term photovoltaic system forecasting. [7] The solar photovoltaic system provides an environmentally friendly source of electricity, but the downside of the solar photovoltaic system is its very low performance. In addition, only 30-40% of solar energy can be converted into electricity by a solar PV system [2]. Therefore, the researcher is often challenged to boost the efficiency of the solar PV system in order to achieve maximum solar radiation [10]

2.9 Energy storage sizing

Storage capacity are generally calculated for short-term supplies only because of the high temporal intermittent associated with generation and limits on storage size [8]. Optimal scale and energy storage allocation aid with a large number of renewables for the operational preparation of the system. When sizing a PV energy storage, different factors and constraints are taken into account. The key problem in maintaining the power quality and reliability is the inherent intermittency of solar power, and battery energy storage can provide a viable solution [9][7]. However, in order to obtain better reports and to allow renewable sources to provide the ancillary services needed by the network, it is important to increase the forecasting time. Since conventional generation plants use a provision of day-ahead dispatch, it is necessary to assess the feasibility of raising the forecast duration for the entire system composed of the renewable generator and storage system to a 24-hour lead time. There is a need to determine the amount of energy storage that can be incorporated with the grid to reduce supply intermittency, as the investment costs associated with energy storage are high and grid-scale storage technologies are yet to mature [1], [7]. Given the high intermittency of solar PV and its sizing-related planning issue, this paper offers an empirical approach to obtaining optimal sizing in a grid-connected system of solar PV generation and battery. This optimum technique of sizing helps to reduce line losses and decrease solar PV generation intermittency. To generate the beta probability density function, historical solar radiance data is used and projected solar PV generation is obtained from it. The different generation is assisted by energy storage for batteries. The proposed simple algorithm provides the optimal dimensioning of the combination of PV-battery[2], [4].

2.10 Modeling of PV storage system

In [13] For-energy generation costs, the use of renewable energy is critical. The use of renewable energy has increased worldwide over the last few years, and this rate is expected to continue. A variety of technological and economic issues must be discussed, aside from the benefits of using renewables. It is difficult to tie them into the current electric grid because of their inconsistent existence. Moreover, once renewable energies have a significant market share, their cost would remain higher than that of traditional energies, posing a technological and economic challenge. As a result, interest in the Battery Energy Storage Device (BESS) as a solution for the incorporation of renewable energy into the electricity grid has been growing. It is difficult to tie them into the current electric grid due to their inconsistent existence. In addition, once renewable energies have a significant market share, their cost would remain higher than that of conventional energies, posing a technological and economic challenge. As a result, the interest in the Battery Energy Storage Device (BESS) as a solution for incorporating renewable energy into the electricity grid has been growing.[4], [14]. There are a wide range of types of technology for batteries, but LIBs are the most used lithium-ion batteries. In terms of energy efficiency, lifespan, and power density, they succeed, but they are not cost-effective, and have a determined life cycle. LIBs are developed in a variety of technology styles and are named after the materials used in their electrodes, e.g. Lithium-Cobalt-Oxide LCO, Lithium-Manganese-Oxide LMO, Nickel-Cobalt-Aluminum (NCA), Lithium-Iron-Phosphate (LFP), Nickel-Manganese-Cobalt NMC, and Lithium-Titanite-Oxide LTO.

2.11 Lithium battery

Due to the worldwide use of cell phones and laptop computers, lithium-ion (Li-ion) batteries are among the most common batteries in the world today. The commercialization of these batteries began in Japan in 1991. However, their history is not as long as traditional batteries that have been manufactured for one and a half centuries, such as lead-acid batteries.

Figure 4: Lithium-Ion battery [5]

In a short period, there are two reasons why Li-ion batteries have become the main type: their outstanding efficiency and their timely arrival to meet the rising demand for consumer electronic goods such as camcorders, cell phones and laptop computers. [15]

Table 1: Comparison of Lithium battery & acid battery [16]

S/N	Parameters	Lead acid battery	Lithium-Ion battery
1	Lithium-Iron phosphate battery	2	3.2
2	Operating voltage of single cell, V	1.9-2.2	3-3.6
3	Discharge cut off voltage of the battery, V	44	42
4	End cell voltage, V	1.8	2.8
5	Battery DOD limit for good battery life cycle	60%	80%
6	Self-discharge	2%	<2%
7	Efficiency, %	85%	95%
8	Cycle life at 80% depth of discharge (DOD), above 27^0C	1500 cycles	6000 cycles
9	High temperature performance	Performance is bad above 27°C	Performance is good till 35°C
10	Operating temperature	-20^0C to 50^0C	10^0C to 65^0C
11	Practical/field tested life time, years	2	4
12	Recharge duration from 20% SOC to 100% SOC	~26 hours from 50% SOC to 100% SOC at 0.1 C-rate	~2 hours from 20% SOC to 100% SOC at 0.5C-rate

2.12 Battery state of charge/discharge

The battery state of discharge SOC is the main constraint for proper battery life. In paper [5The maximum charge and discharge power to be guaranteed by the compensating system are checked, with its State of Charge (SOC) being the only restriction for the BESS. A battery's charging state is the energy available, expressed as a percentage of its rated power. This is a typical method of charge control where charging and discharging are directly linked to the current drawn or supplied by the battery [14], [[13], [17]]. A full discharge or overcharge of the battery should be avoided in order to extend the battery life and maintain its health; therefore, the state of charge of the battery should be kept within the proper limits and correctly estimated at each control interval. For this research, the state of charge restriction imposed is the following: 20% < SOC < 90%. For most forms of storage systems, this interval allows for optimum power exchange and avoids either a substantially large discharge or an overcharge. The purpose is to force the actual power supplied or absorbed by the BESS to be equal to the ideal reference power when the state of the charge interval range is specified. [2], [16].

$$SOC = SOC_o - \int_0^t (\delta)\, dt \qquad (10)$$

2.12.1 SOC estimation method

[13] The main features to be taken into account when estimating the state of charging in some applications are accuracy, performance, and robustness. The transducer errors are determined by battery current and voltage. With various operating modes and battery lifespan, battery habits change. Therefore, in the estimation algorithm, the calculation of modeling errors must be as small as possible.[13], [17]. The state of the charge estimation algorithm should take less time to minimize computing power. Different approaches such as book-keeping and adaptive systems are currently available for measuring the charge status. Comparison analysis is carried out on various methods of estimating the state of charge. The following table illustrates the advantages and drawbacks of various methods of measuring charge status. [14], [15].

Table 2: State of charging estimation method [14]

Methods	Advantages	Disadvantages
Discharge test	Easy and accuracy	Energy loss, time intensive, offline, modifies the battery state,
Coulomb counting	Accurate for flawless current measurement	Sensitive to parasite reactions
Ampere Hours computing technique	More accuracy	temperature changes are not taken into consideration
OCV	Online, cheap	Need long rest time
Impedance spectroscopy	Sensitive to SoC variation	Temperature sensitive
Neural network	Online, do not need previous knowledge	Large number of training samples
Kalman filter	For all battery systems	Need strong hypothesis
Fuzzy Logic	Online, robust	Large amount of memory in real world application

2.12.2 Comparison of different state of charging estimation ways

In [14] The State of Charging Estimation Algorithm should be less time-consuming to reduce computing power. Various approaches such as bookkeeping and adaptive systems are currently available for measuring the charge status. Comparison analysis is conducted on a separate state of charge calculation methods. The following table illustrates the advantages and disadvantages of various methods of measuring charging status.

2.12.2.1 Ampere hours computing technique

This is the most commonly used and simplest way to measure the battery's accurate status and is defined by the equation below where SOC(t) is the charge state of the battery at time t, SOC(t-1) is the initial charge state of the battery, iBatt is the charge-discharge current, and cBatt is the battery power. The state of charge variation is measured in Ah counting by integrating the current of the battery at a given time by the power of the battery [15]. If the initial state of charge is reasonably precise, an accurate state of charge is calculated. It has many drawbacks, however, so it is extremely important to provide an accurate initial charge state measurement since it cannot automatically get the exact initial charge state. Even small errors in current measurement result in a significant change in the state of charge calculation over a time, due to the incorporation of current. Constant battery capacity is considered and the impacts of a lifespan, existing dependencies, and changes in temperature are not taken into account. [14][13].

$$SOC(t) = SOC(t-1) + \int_0^t \frac{iBatt}{cBatt} x dt \qquad (11)$$

2.12.2.2 Combination of Coulomb counting and fuzzy logic

A state of charge measurement is necessary to know the charge level of the battery. Different measurement methods are involved to find the state of charge. A mixture of coulomb counting and fuzzy logic method is the proposed scheme [14]. In the figure below, the device model is depicted as a block diagram. The block diagram shows us the undercharging state of the battery's charge measurement. To measure the actual charging state of a battery, a battery measurement unit is used. The state is then calculated using a technique of coulomb counting, and the result obtained is compared to the actual state of charge. The error value calculated and the change in error value is given as inputs to the fuzzy logic method. To adjust the coulomb counter to provide a new state of charge value, the output from the fuzzy method is used [13][15].

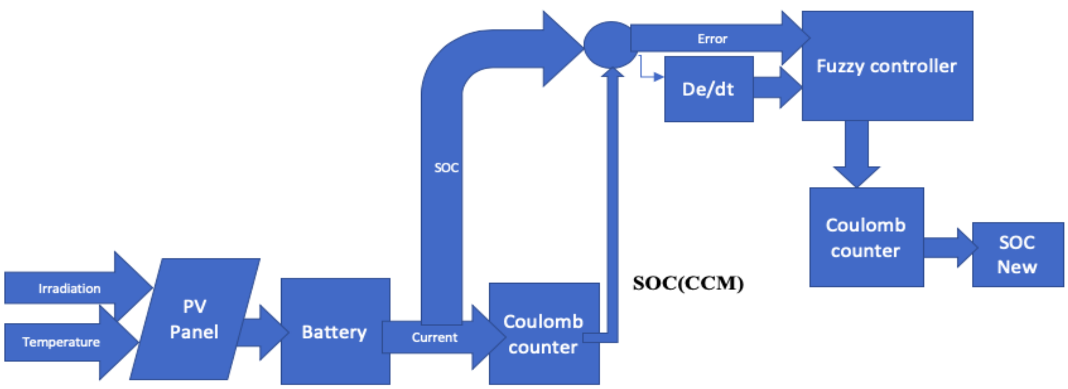

Figure 5: Combination of coulomb counting fuzzy Logic system block diagram

Coulomb counting, where measurement is performed as follows, is the easiest and often preferred way to find the state of charge where

$\mathrm{i(t)}$ the current in amps

$\mathrm{SOC(0)}$ is the initial value of state of charge.

This technique is very easy and is related to the relationship shown in the figure below. Nonetheless, it suggests certain limitations such as SoC (0) must be understood; i(t) is the only signal to be used; thus, if errors arise in the measurements, the measurement must be reset promptly. The second drawback is the most challenging obstacle to contend with. Filtering the noise from the current transducers will prevent the expected error. It is possible to know the initial value of the charge state before the real time applications. Current transductors with high accuracy are available in battery management systems. Dynamics in a fuzzy system can be modeled instead of complex expressions by means of a fuzzy rule base, which contains a collection of fuzzy laws. It is possible to explain different backgrounds in one rule using fuzzy logic. It creates properties with enormous precision [15]. Fuzzy logic is therefore used here for the calculation of the state of charge. Using a battery measurement unit, the actual charging state of the battery is determined. Then the state of charge is obtained using the relation shown in the above expression using a coulomb counting process, then a comparison of the actual state of charge and a measured state of charge error generates some error. To improve the accuracy of the Coulomb Counting Method (CCM), a fuzzy logic way is integrated into the system. Error and error corrections are taken as Fuzzy Logic System input variables [6]. The membership functions are shown in Figure 6 for error, segmenting the error into 3 fuzzy subsets that are small, medium, and high in the range from -9 to -1 from 0 to 12. [13]

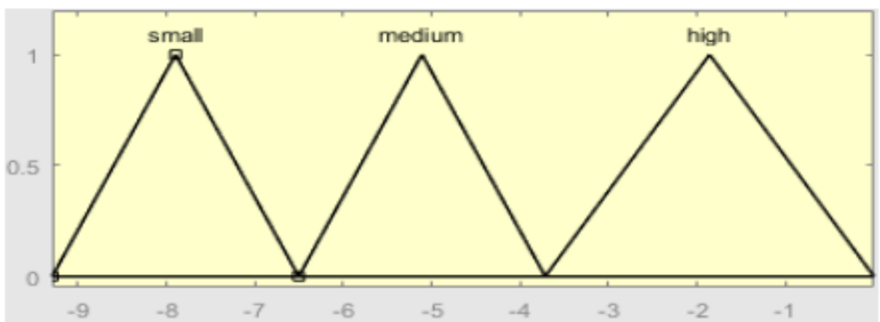

Figure 6: Membership function of charge error [14]

2.12.3 Energy storage and cost constraints

The battery energy storage is implemented to act as an energy buffer to help the utility-scale PV system become a predictable and controllable source to mitigate the adverse effects of grid integration of large-scale PV plants. Recent research has shown that battery storage could reduce the ramp rate and reduce the fluctuation of the output power of PV systems. In addition, as an advanced battery technology, the LiFePO4 battery can achieve high power and energy density with a long cycle life and good safety efficiency. This form of battery has therefore gained a lot of attention in the applications of the grid. Nevertheless, in various applications, the battery life and efficiency vary greatly. A systematic performance study of LiFePO4 batteries is therefore required to design battery systems for both PV plant owners and battery manufacturers. [7]**.** Lithium-ion batteries, which have high density, high round trip performance and fast-ramping capability, are well suited for frequency control among the currently available battery technologies. Nonetheless, many challenges impede the widespread introduction of lithium-ion BESSs. While lithium-ion batteries are under continuous development and their costs are expected to decrease dramatically in the future, this energy storage solution is still seen as an investment risk because stakeholders cannot easily assess efficiency, longevity and cost-effectiveness. [8]. Li-ion battery prices and costs of power electronics have decreased dramatically in recent years and are expected to decrease further, making the BES a more economically interesting choice. The BES profitability in outage reduction was suggested in the current work primarily in case studies such as BES were proactively used to avoid the outage conditions induced by excessive peak feeder loads [9]. The Lithium iron phosphate batteries have significant advantages such as improved discharge, charging and performance, as per Table I, Lead-acid and Lithium battery comparison. A longer life span is a key feature that makes this form of battery economically viable and, in addition, it has the potential to sustain power in a deep cycle. The LiFePO4 batteries are cost-full on the market, but in terms of sustainability, there is no maintenance needed over the life of the device, and they last longer and these characteristics make them a worthwhile investment and therefore become a long-term solution for energy storage.

2.13 Sizing of the battery bank

The amount of rough energy storage E_r required is equal to the multiplication of the total power demand and the number of autonomy days.

$$E_r = E\,T \tag{13}$$

where *T:* Number of autonomy days

E: Total power demand to back up the plant

For safety, the result obtained is divided by the maximum allowable level of discharge (MDOD)

$$E_s = \frac{E_r}{MDOD} \tag{14}$$

where *MDOD:* Maximum Depth of Discharge (0.70) in our case

E_r*:* Safety energy in MWh

We need to make a decision at this time about the nominal voltage of each battery $(V_b)$to be used in the battery bank. By dividing the safe energy storage needed by the DC voltage of one of the selected batteries, the battery bank capacity required in ampere-hours can be evaluated. [17],[18]

$$C = \frac{E_s}{V_b} \tag{15}$$

Another decision must be taken on the capacity (C_b) of each of the batteries of that bank, according to the number obtained for the capacity of the battery bank. The total number of batteries$(N_b)$is obtained by dividing the battery bank's capacity C in ampere-hours by the capacity of one of the batteries(C_b)selected in ampere-hours. [5].

$$N_b = \frac{C}{C_b} \tag{16}$$

The connection of the battery bank can be then easily figured out. The number of batteries in series equals the DC voltage of the system divided by the voltage rating of one of the batteries selected:

$$N_s = \frac{V_{dc}}{V_b} \tag{17}$$

Then number of parallel paths $(N_p)$is obtained by dividing the total number of batteries by the number of batteries connected in series:

$$N_p = \frac{N_b}{N_s} \quad (18)$$

Once the sizing of the battery bank is made available, we proceed to the next system component but in this study, we will not size other components because the case study plant is already in use. We will use the same size of converter in order to be cost effective [5], [19]

2.14. Sizing charge voltage controller

It regulates the flow of current according to its purpose. The maximum current provided by the battery banks, as well as the maximum load current, must be able to withstand a good voltage regulator. The scale of the voltage regulator can be obtained by multiplying the protection factor F of the short circuit current of the battery bank. The consequence is that the voltage regulator's rated current is given [19][20].

$$I = I_{sc} N_p F_s \quad (19)$$

where I_{sc}: Short circuit current of battery bank

F_s: Safety factor

The current needed for the battery bank will be given by the total power needed over the total maximum voltage that is needed to be injected into the system.

2.15 Energy transition radiation to MW generation

This study is mainly focused on solar energy radiation behaviors that later will give a big picture of how the energy is being affected by solar radiation unreliability. The transition from solar radiation to MW generation will be done from the expression below:

$$P = \frac{P_r I_d}{R_m} \quad (20)$$

Where P_r: Plant rated power

I_d: Difference in solar radiation in KWh/m^2/day (Max & Min)

R_m: Possible Maximum solar radiation in KWh/m^2/day

The rated generation refers to the installed capacity of the GW Rwamagana PV planet, that is the energy that would be generated by this PV if it receives maximum possible radiation which is 8.5MW. Differences in solar radiation will be calculated by referring to the maximum and minimum possible average solar radiation that have been taken from three different stations (Rwamagana, Kanombe, and Kayonza

3 Data collection and analysis

3.1 Data collection

In this research, we will be having data from three different sources. The first are data that have been collected from Meteo Rwanda where recent data from two and half years till now are taken into consideration. These data have been taken from Rwamagana station to ensure the coverage of the region where case study (Rwamagana PV plant) is located. The second source contains the data that are found in the main reference paper that has been used in this research which are the outcomes from using the modal at Kigali station (Kanombe). Here data have been collected based on the Meteorological Radiation Model (MRM) which is the estimation of hourly and daily solar radiation on inclined surfaces by determination of the corresponding hourly values on the horizontal plane. The last source of data is the data that have been collected from GW Rwamagana PV plant. The data were about voltage ratings, converter specification, solar radiation they are receiving as well as startup and shutdown time for me to determine the days of autonomy of the plant. 182. 8 1 295039

Table 3: Average global solar radiation at Kigali site since 1974-1993 on monthly basis: G KWh/m^2/day [11]

S/N	Year/ Month	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Gmin	Gmax	Standard Deviation
1	1974	4.947	5.039	4.503	4.498	4.428	4.230	4.144	4.208	4.810	5.124	4.428	4.661	4.144	5.124	0.332
2	1975	5.106	4.872	4.283	4.498	4.166	4.247	4.212	4.447	3.928	4.268	4.918	4.753	3.928	5.106	0.360
3	1976	4.998	4.490	4.868	4.549	4.057	4.859	4.487	4.708	4.583	4.828	4.610	4.604	4.057	4.998	0.246
4	1977	-	4.475	-	4.067	4.590	4.493	5.015	4.548	4.681	4.809	4.322	4.827	4.067	5.015	0.271
5	1978	4.911	4.878	4.427	4.412	4.757	4.745	4.878	4.890	4.894	4.826	4.592	4.239	4.239	4.911	0.230
6	1979	4.654	4.446	5.049	4.285	3.868	4.622	4.128	4.917	4.961	4.651	4.687	4.499	3.868	5.049	0.347
7	1980	4.705	4.722	4.650	4.538	4.079	4.975	5.007	5.299	4.299	4.092	4.549	4.961	4.079	5.299	0.374
8	1981	-	4.844	-	4.478	-	-	-	-	-	-	-	-	4.478	4.844	0.259
9	1982	-	-	4.905	4.253	4.150	4.642	4.986	4.671	4.557	4.397	4.374	4.794	4.150	4.986	0.278
10	1983	4.788	4.754	4.422	4.246	4.726	4.672	4.684	4.435	4.978	4.360	4.591	4.290	4.246	4.978	0.226
11	1984	4.301	4.765	4.780	4.419	4.861	5.166	4.612	5.037	4.944	4.660	4.111	4.867	4.111	5.166	0.309
12	1985	-	4.757	4.217	4.180	4.202	4.392	4.705	5.411	5.182	4.445	4.574	4.610	4.180	5.411	0.398
13	1986	4.765	4.834	4.470	4.047	4.215	4.913	5.091	-	-	4.856	4.240	4.353	4.047	5.091	0.356
14	1987	4.565	4.062	4.988	4.684	4.447	4.489	-	-	-	-	-	4.323	4.062	4.988	0.289
15	1988	4.474	4.771	4.617	4.114	4.510	4.955	4.566	4.365	4.535	4.633	4.581	4.590	4.114	4.955	0.204
16	1989	4.504	4.809	4.503	4.540	4.358	4.959	5.110	5.161	4.776	4.681	-	-	4.358	5.161	0.273
17	1990	5.349	4.308	4.477	4.861	4.672	5.004	5.396	4.936	4.834	4.746	4.702	4.500	4.308	5.396	0.328
18	1991	4.867	4.912	4.893	4.487	4.092	4.430	4.959	5.208	4.927	-	-	-	4.092	5.208	0.345
19	1992	4.772	4.638	4.742	4.732	4.620	4.624	5.332	5.507	-	4.736	4.791	4.423	4.423	5.507	0.320
20	1993	4.489	4.849	4.849	4.922	4.507	4.430	5.746	5.230	5.584	4.898	4.541	4.533	4.430	5.746	0.437

The above table shows the monthly averaged global solar radiation that has been taken at Kanombe in Kigali city over the period of 1974-1993.The data have been pulled out from reference paper [9]. From the tale all the green shade cells represent the data that have been take at different time but always greater than 5.00KWh/m^2/day. The Yellow cells stands for the data collected at the same station but they were always less than 4.00KWh/m^2/day that is to mean the minimum possible solar radiation was 3.00KWh/m^2/day. When it goes to the possible minimum and maximum yearly global solar radiation, the blue cells reveal that the minimum and maximum possible occurred were 3.868KWh/m^2/day and

5.746KWh/m^2/day respectively that have been occurred in 1979 and 1993 respectively. On the side of the data deflection and how much data are being changed over the time, the figure in black cells 0.204 and 0.437 represent the yearly standard deviations that have occurred in1988 and 1993 respectively

Table 4: The Min & Max of monthly average global solar radiation sine 1974-1993 [11]

Yearly Avera	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Gmin (1979)	Gmax (1993)
Average	4.762	4.696	4.647	4.441	4.384	4.676	4.837	4.881	4.780	4.648	4.538	4.578	4.169	5.147

Table 5: Average global solar radiation on Rwamagana site sine 2018-2020 on monthly basis: G KWh/m^2/day [11]

Description	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Gmin	Gmax	Stan d dev	Yearly mean
Per month average value2018	-	-	172.5	162.2	177.3	-	199.7	188.4	192.8	190	173.4	156.7	156.7	199.7	14.508	177.3
Per month average value2019	200.8	202.2	160.8	-	167.8	170.9	-	-	-	-	-	119.0	119	202.2	30.582	169.35
Per month average value2020	94.5	149.3	103.4	106.3	-	176.3	171.9	-	-	-	-	-	94.5	176.3	36.668	127.8
Per day value 2018 (KW/m2)	-	-	5.565	5.232	5.719	-	6.442	6.077	6.219	6.129	5.594	5.055	5.055	6.442	0.468	5.719
Per day value 2019 KWh	6.693	6.740	5.360	-	5.593	5.697	7.451	6.387	7.385	6.763	5.732	3.967	3.967	7.451	1.018	6.387
Per day value 2020 KWh/m2	3.150	4.977	3.447	3.543	-	5.877	5.730	-	-	-	-	-	3.150	5.877	1.222	4.260
Per day average value KWh/m2	4.922	5.858	4.790	4.388	5.656	5.787	6.541	6.232	6.802	6.446	5.663	4.511	4.388	6.802	0.815	5.725

The above table contains monthly averaged global solar radiation of the data have been taken on Rwamagana station over period of 2018-2020.The aim of taking this statin was to ensure that we covering the area where GW Rwamagana PV plant is located. The green color in the table stands to the data that are above 5.00KWh/m^2/day and the purple cells data stand for data that are in the range of 3.00KWh/m^2/day.

Table 6: Averaged Max &Min global solar radiation over 2018 – 2020 on monthly basis

Item	Gmin	Gmax	Yearly mean	Stand dev
Per day value 2018 KWh/m2	5.055	6.442	5.719	0.468
Per day value 2019 KWh	3.967	7.451	6.387	1.018
Per day value 2020 KWh/m2	3.150	5.877	4.260	1.222
Per day average value KWh/m2	4.388	6.802	5.725	0.815

The above table shows the different maximum and minimum global solar radiation taken from different years. The data have been summarized from calculations done from the data taken from different stations. The table also consists of yearly mean values that have been calculated after taking Gmax and Gmin values.

3.2 Data analysis

All the data in this study have been analyzed and interpreted by using google sheet tool. That is to mean tables, charts, calculations and graphs are in the form of google sheets.

3.2.1. Monthly basis interpretation

Down is a plot of global solar radiation that has been taken from 1974 to 1993 over Kanombe station where the re-interpretation of data taken from reference paper has been done expecting to get the same results but in different form.

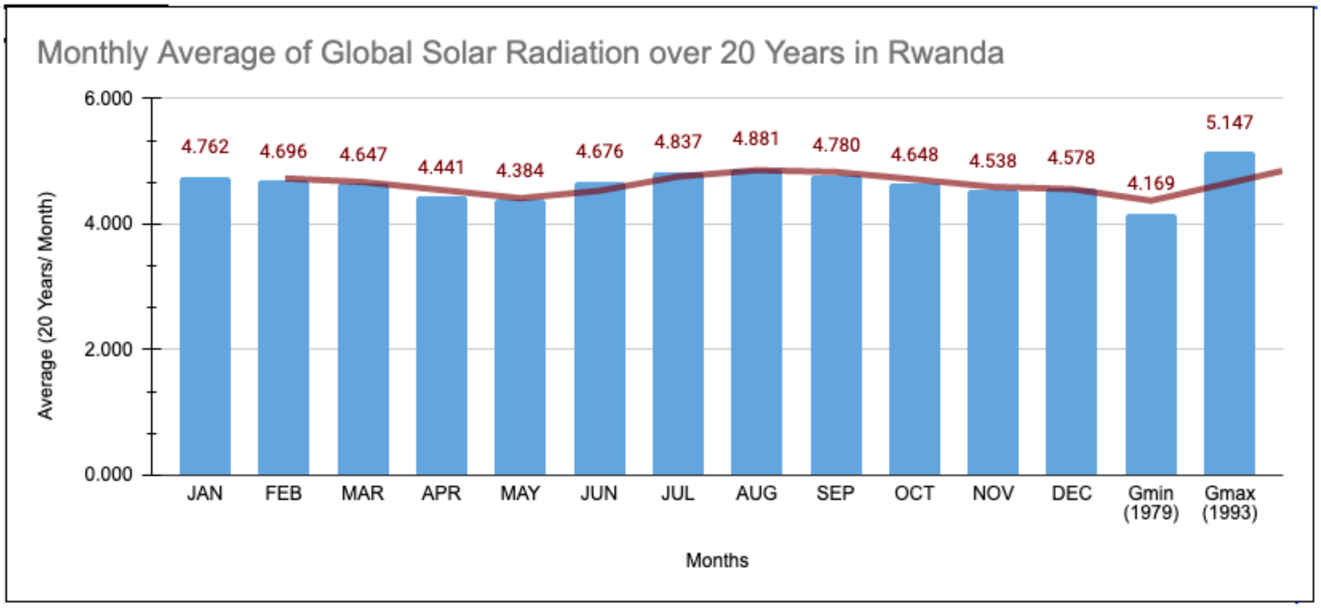

Figure 7: Monthly Averaged global solar radiation over 20 Years in Rwanda at Kanombe station [11]

The above figure shows the average global solar radiation calculated from each and every month in the rage of twenty years. These data have been collected on Kigali, Kanombe station by applying the Meteorological Radiation Model. From the graph, it is clear that the lowest monthly averaged solar radiation occurred in April and May which be 4.441 and 4.384 KWh/m^2/day respectively where the lowest value was 4.384KWh/m^2/day. The Maximum monthly average value of solar radiation has been occurred in August and it was 4.881KWh/m^2/day. On the other hand of yearly global solar radiation, the maximum Gmax and Gmin are 5.147KWh/m2/day and 4.169KWh/m^2/day respectively. If you look at the difference between the two numbers, there is no much difference in terms of figures but it gives a significant impact on the solar PV output power .This is because the solar panels are very sensitive to the change of the input which is solar radiation that is to mean every radiation decimals drop or increase will result in rapid drop and rise of the plant output voltage of the plant. Combining the monthly average values with yearly global solar radiation values, the minimum Gmin and maximum Gmax have a significant difference in terms of figures but in terms of the meaning to the study, this is not trustful results because these results are on a single year basis which is not more generalized over whole sample. That is why in this study, we will take the average values of the all samples taken from different station for us to have the accurate results.

3.2.2 Global solar radiation on yearly basic

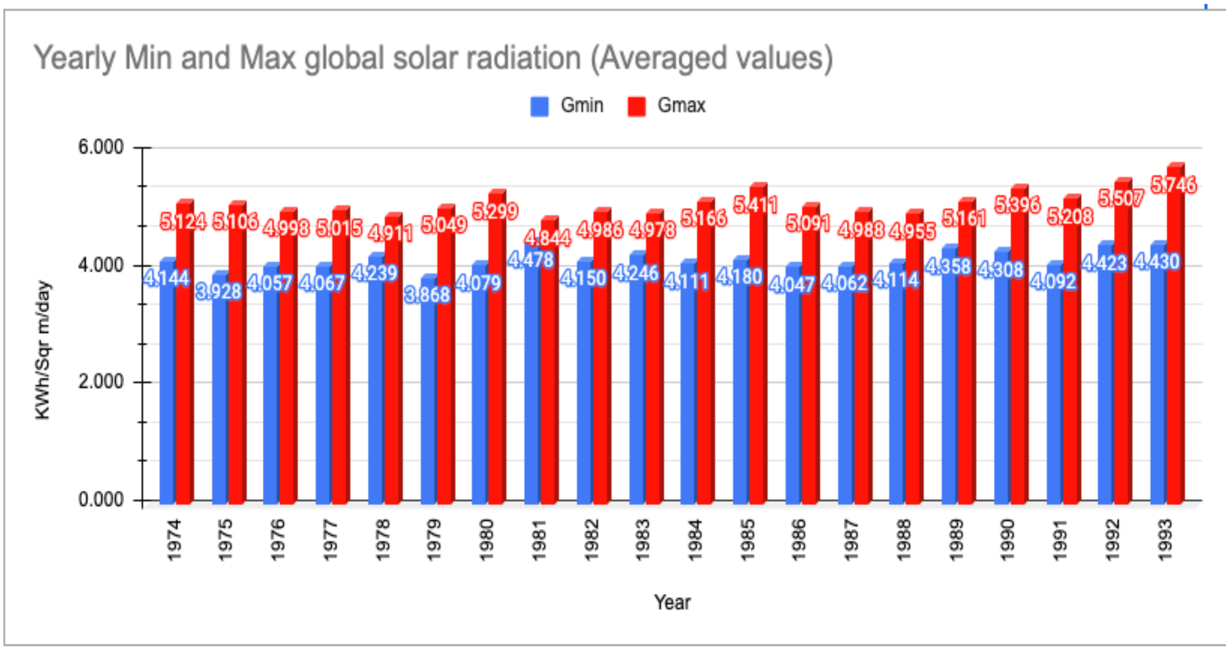

Figure 8: Yearly Min and Max global solar radiation (Kanombe station) [11]

The figure 8 shows the plotting of yearly maximum and minimum global solar radiation that has been calculated over twenty years data taken from Kanombe statin over the period of 1974 to 1993. The graph shows that the lowest solar radiation value occurred during the rainy seasons in April and May, but in July and August the greater value occurs very precisely in the dry seasons. Gmin 3,868 KWh / m^2 / day is the theoretical lower of the solar radiation obtained on the horizontal terrain, referring to that graph, and this occurred in 1979 and the Gmax 5,746 KWh / m^2 / day is the maximum amount of solar received on the horizontal surface and was in 1993. April is Rwanda's wettest month, with the cloud covering a major factor that impedes the maximum number of solar rays to be obtained. This is an important factor for the design of a solar power plant that needs to be taken into account. Since these findings have been taken a long time ago, we will need to equate them with the current data from the new and upgraded stations, where during the analysis of results the deviation from recent and old data must be taken into account.

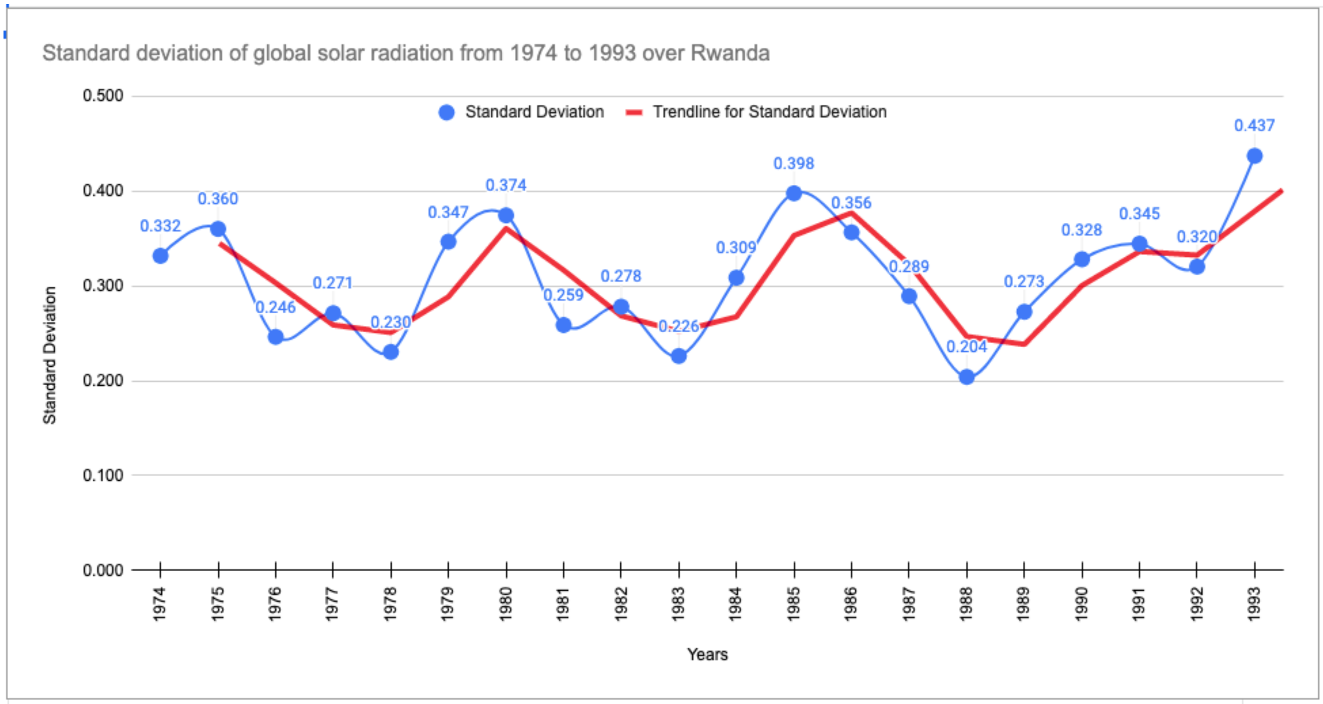

Figure 9: Standard deviation of global solar radiation at Kanombe station [11]

The above figure shows the standard deviation and its trending flow. As per information from figure 9, the yearly standard deviation shows that the smallest deviation is 0,204 that occurred in 1988. The maximum standard deviation was 0.437 and this was in 1993. Even though the difference is seemingly to be quite low, it has a significant role during calculation of the PV output power that will no doubt affect the PV plant performance Having a look on the trend, many of the deviation's values oscillate within the range of 0.200 and 0.400 over the period of twenty years. That is to mean the frequency of occurrence where the value is out of range is relatively low compared to the value inside. That is to mean the 0.200 deviation difference is not very high for us to confirm that there is high fluctuation of solar radiation over twenty years. Therefore, we can trust our climatic behavior during sizing the backup energy storage.

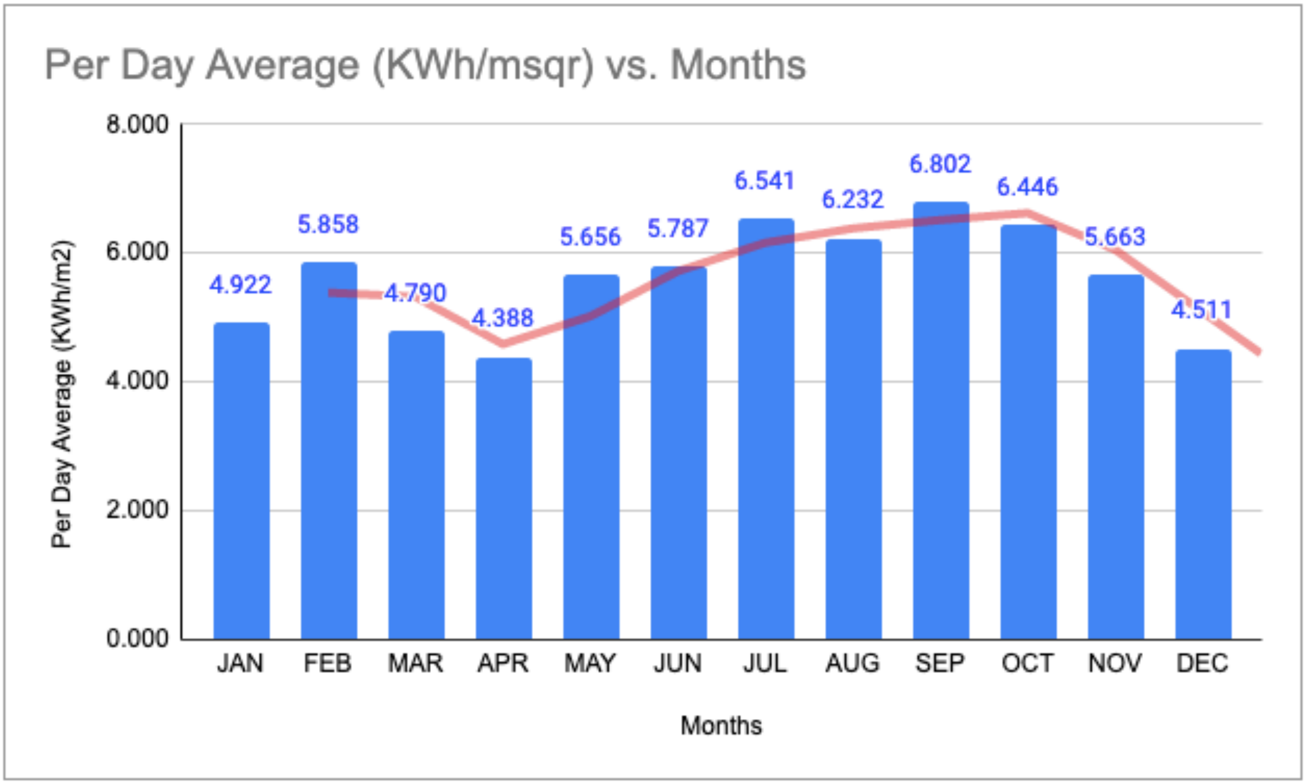

Figure 10: Per day average KWh/m^2/day vs months (Rwamagana station)

The above figure shows the results plotted from the data that have been collected from Rwanda Meteo for the recent two and half years 2018 to 2020 June. Compared to the results over the last twenty years, it is clear that the numbers of KWh/m^2/day have been changed significantly. The lowest value in April has dropped from 4.441 to 4.388 KWh/m^2/day and the highest value is raised from 4.881 to 6.802KWh/m^2/day in May. The maximum monthly average has occurred in September, which is 6.802 KWh/m^2/day instead of occurring in August and July as normal. July and August have 6.541 and 6.232 KWh/m^2/day which are not far from the overall maximum of September. The difference between the lowest and the highest monthly averaged solar radiation occurred over these two and half years is 2.414KWh/m2/day which is a big fluctuation to change the output of photovoltaic generation plant. From the results, it is clear that the climate has changed over the last twenty years.

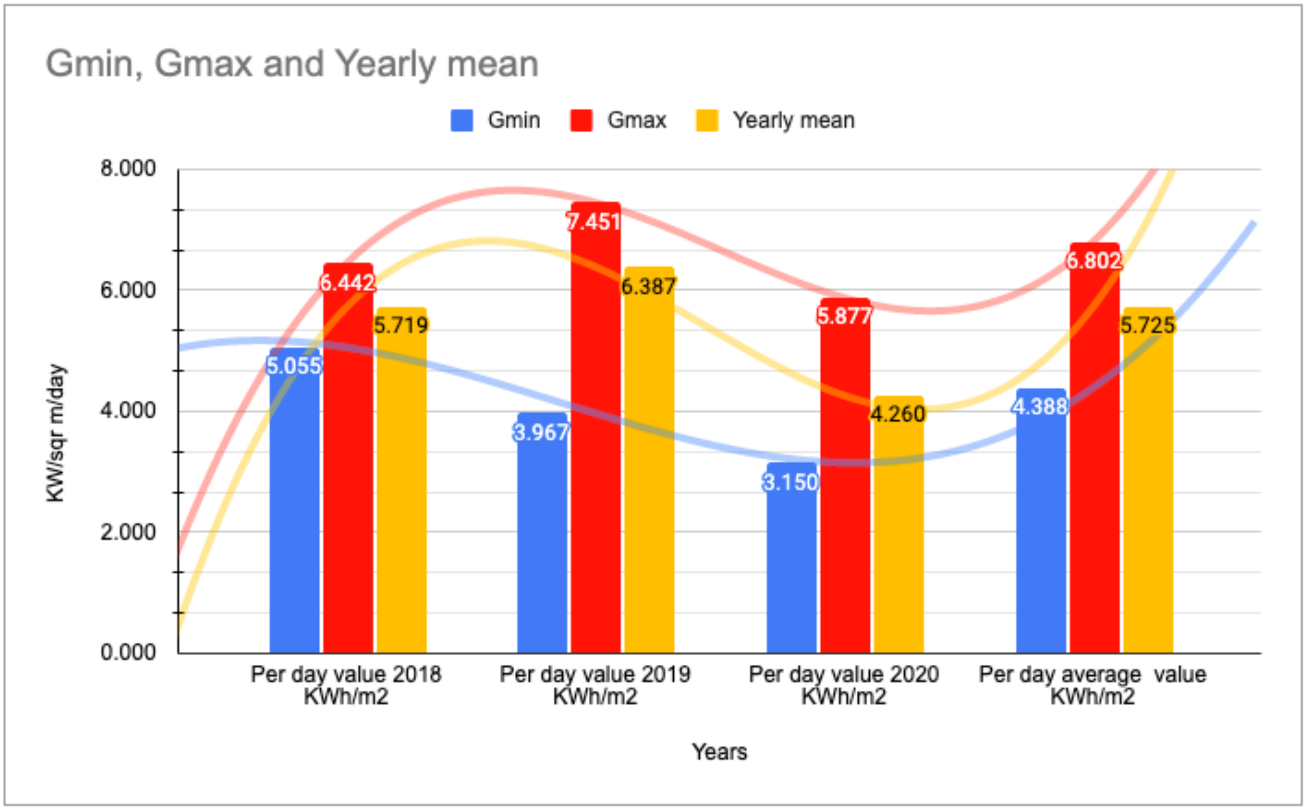

Figure 11: Yearly Min, Max and Mean global solar radiation (Rwamagana station)

By referring to the Global solar radiation over one specific year , it is clear that from the above figure that maximum global solar radiation was occurred 7.451 KWh/m^2/day in 2019 and the minimum global solar radiation occurred was 3.150 KWh/m^2/day in 2020.The yearly mean values indicate that there is a serious inconsistency of solar radiation for each year but the difference in number revealed that we can trust the results from the assessment because the discrepancies in solar radiation are not high . Since the data has been analyzed on a yearly basis. The sample is narrow which is hard to conclude from these results. We need a combination of different weather stations for accuracy before drawing conclusions.

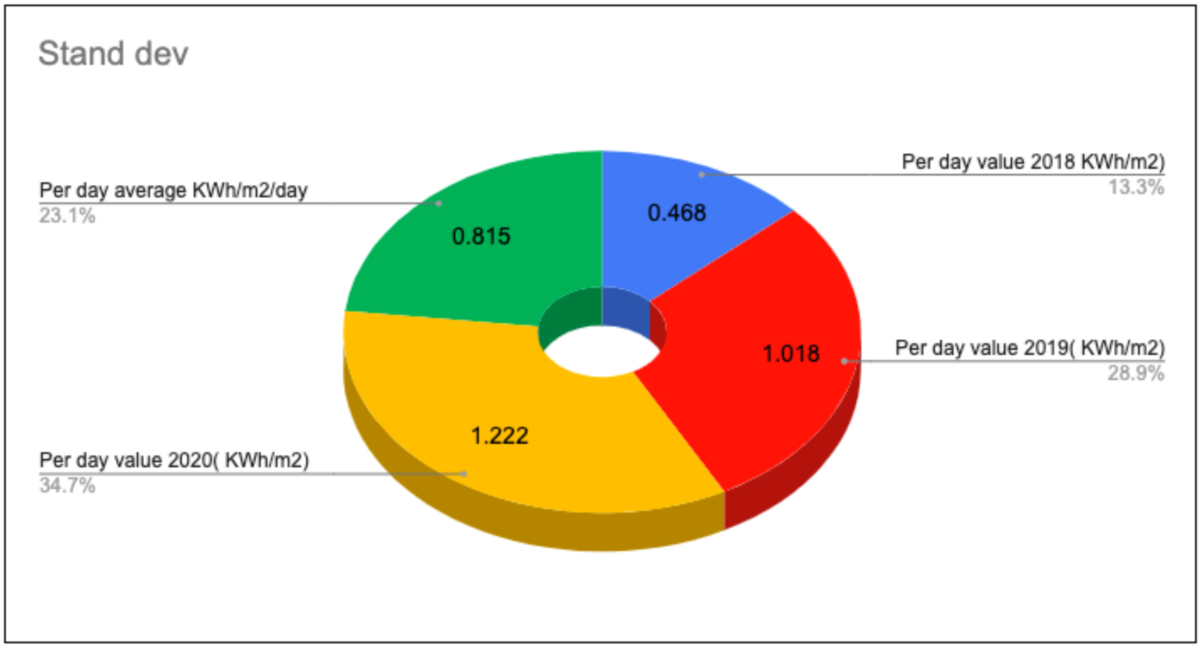

Figure 12: Standard Deviation of global solar radiation (Rwamagana station)

As per standard deviation pie chart, it is clear that the deviation is somehow high. That big difference is due to the fact that the sample of two and half years is not big enough to decrease the value. This situation is worse in 2020 since in this year we took data for only six months which is a small sample as well. The average value meets the requirement because the more we get less standard deviation the more accurate we are.

3.3 Data taken over Kayonza station

Table 7: Average global solar radiation on Kayonza station over 2018-2020 monthly basis KWh/m^2/day

Years	JAN (31)	FEB(28 /29)	MAR(31)	APR(30)	MAY(31)	JUN(30)	JUL(31)	AUG(31)	SEP(30)	OCT(31)	NOV(30)	DEC(31)	Gmax	Gmin	Stand.Dev
2018	169.856	120.299	178.212	157.099	204.599	200.574	230.994	198.009	170.553	109.657	171.962	170.634	231.0	3.5	34.2
2019	184.535	180.336	191.303	150.093	188.369	194.057	188.981	188.896	191.478	184.434	180.369	171.227	194.1	150.1	12.1
2020	164.666	139.458	167.005	146.860	195.179	179.084	182.158	-	-	-	-	-	195.2	139.5	19.7
2018	5.479	4.296	5.749	5.237	6.600	6.686	7.451	6.387	5.685	3.537	5.732	5.504	7.5	3.5	1.1
2019	5.953	6.441	6.171	5.003	6.076	6.469	6.096	6.093	6.383	5.949	6.012	5.523	6.5	4.5	0.4
2020	5.312	4.981	5.002	4.467	6.296	5.969	5.876	-	-	-	-	-	6.3	4.5	0.7
Average	5.581	5.239	5.641	4.902	6.324	6.375	6.475	6.240	6.034	4.743	5.872	5.514	6.5	4.7	0.6

The above figure shows the data that have been taken from the Kayonza station which is not far from Rwamagana where the case study of this research is. Comparing all minimum monthly average solar radiation from all three stations we can see that 4.902,4.388 and 4.384 $KWh/m^2/day$, there is no much difference that is to mean the solar radiation over eastern part of Rwanda plus Kigali is no quite different as its average is 4.225$KWh/m^2/day$. From these figures we can still trust our results. Let have a look on the side maximum monthly average solar radiation 4.881,6.802 and 6.475 $KWh/m^2/day$ for Kanombe, Rwamagana and Kayonza stations respectively, the there is a difference but their average 6.053 $KWh/m^2/day$. The lowest yearly global solar radiation occurred at these stations (Gmin) are 4.169,3.15 and 4.7 $KWh/m^2/day$ with their average is 4.006 $KWh/m^2/day$. On the other hand, the highest possible yearly global solar radiations are 5.147,7.451 and 6.5 $KWh/m^2/day$ with a computed average of 6.366 $KWh/m^2/day$. By computing the difference between the two, we can see that 1.828 $KWh/m^2/day$ will be the monthly average solar radiation taken from all stations. On the side of the yearly global solar radiation, the difference is 2.360 $KWh/m^2/day$ which looks somehow high compared to the monthly averaged value. Table below shows computed Differences for Global solar radiation G and monthly averaged solar radiation over Kanombe, Rwamagana and Kayonza.

Table 8: Max, Min, Gmin and Gmax average values over four station

Station	Max(Average)	Min(Average)	Gmin	Gmax
Kanombe	4.881	4.384	4.169	5.147
Rwamagana	6.802	4.388	3.15	7.451
Kayonza	6.475	4.902	4.7	6.5
Average	6.053	4.558	4.006	6.366
Difference		1.495		2.360

Since the difference 1.495 $KWh/m^2/day$ was computed over twenty-three years, it is more meaningful than 2.360$KWh/m^2/day$ as this was taken over into specific year. In this study the 1.828$KWh/m^2/day$ will be taken into consideration when sizing energy storage system.

3.4 Sizing the energy backup storage

3.4.1 Prerequisites

As per data collected from Rwamagana GW solar PV, the site at which the plant is located, they are receiving 5kwh/m^2/day so at the radiation that provides minimum required conditions, inverters will start to convert energy and feed it into the grid. The voltage they are generating is being provided by 20 panels of 300Wp that are connected in series. This plant has an inverter whose type is SC900CP -XT and its maximum and minimum input voltages are 562 and 1000V respectively. The Rwamagana GW Rwamagana solar plant starts at 6:50 and shuts down at 5:45 giving the operating hours of 10hours and 55 minutes.

3.4. 2 Backup energy required

As we have seen from the results interpretation, a 1.495 KWh/m^2/day is the generation gap that we need to cover for the plant to stay connected to the grid during all operating hours. Equation (19) gives us the real energy that is being generated at possible maximum solar radiation. This gives us 6.4MW. Since the installed capacity of GW Rwamagana is 8.5MW, the difference between the maximum possible generation and installed capacity will be 2.1MW which is equivalent to the energy that is needed to be stored to back up the system to operate on its installed capacity. Since the system will be reliable for all plant running hours, the amount of rough energy storage required is equal to the multiplication of the total power demand and the number of autonomy days, which results in 23.1MWh. For safety concern, we will need to involve the battery strength in terms of charging and discharging constraints. From the equation (14), the safety energy Es is 33MWh. Since we have the amount of energy that is required to back up the system, we will need to calculate the capacity of the battery bank that is able to store that energy. From equation (15), the capacity of the battery bank C is 687500Amph.Now we have the capacity of the battery bank C, we will need to calculate how many batteries in the bank. We have chosen,48V 300Ah LiFePO4. Calculating the total number of the battery (N_b) needed to meet the battery bank, from equation (16) we will get 2292 batteries. The power that will be generated by this battery bank will be injected into the grid through the converter "Sunny Central 900CP XT" whose minimum and Maximum input voltage are 562/1000VDC respectively. This converter starts converting whenever the input voltage reaches to it minimum possible which is 562VDC. For our backup energy storage, we need to inject at least the voltage which is less or equal to its Minimum that will keep the converter on even though the plant voltage drops at some point. The arrangement of the battery bank is made in such way that the Serie string batteries generate the at least the minimum input V_{DC} for a converter which is $562V_{DC}$. The number of series connections Ns will be calculated from equation (17) and from there we will have 11.70 batteries in one string. Since the battery should be a complete component, the number 11.70 batteries will be rounded to 12, hence we will need to connect 12 batteries in series to generate 562 V_{DC}. Having number of batteries on one Serie string, we are able to calculate the number of the parallel connections N_p. This can be calculated from the equation (18) and it can be obtained by dividing the total number of the batteries for the battery bank divided by the number of Serie connections N_s that results to 190.5 parallel connections. Since the connections should be a complete number, the number 190.5 batteries will be rounded to 191, therefore, we will need to connect 191 batteries in parallel to generate the required amount of battery bank current. The current needed for the battery bank will be given by the total power(2.1MW) needed over the total maximum voltage(562) that is needed to be injected into the system that is 3737A.The real total number of the batteries needed for the battery bank will be calculated by multiplying the series connections N_s by the parallel connections $N_p$which gives a total of batteries 2292 batteries.

3.4.3 Sizing a charge controller

It regulates the flow of current according to its purpose. The maximum current provided by the battery bank as well as the maximum load current must be able to withstand a good voltage regulator. The size of the voltage regulator can be obtained by multiplying the protection factor F (1.25) by the short circuit current of the modules connected in parallel. The consequence is that the voltage regulator's rated current is given. The short circuit of this battery is not mentioned on the data sheet but it can be calculated as we have short circuit protection, which is 5% of its peak discharge current. This will give the short circuit current equals to 262.5A. From the equation (19), the charge controller will be rated in amps and the value will be 62672A. Since the charge controller will be rated in amps, the value 68901A will be enough to withstand the total current that will be needed by this storage system and we will be able to add more batteries in case we need to upgrade the system.

4 Results and discussions

From the analysis made during data interpretation, we have realized that the highest possible monthly average solar radiation that is being received at the recent stations where solar radiation data were taken from was 6.802KWh/m^2/days, the possible minimum value was 4.388KWh/m^2/day respectively. From the data that have been taken from the Gw Rwamagana PV plant, the site at which the plant is located, needs receive at least 5KWh/m^2/day solar radiation as a minimum for the converter to start working. It shows that there will be a time where the plant will be generating power lesser than the rated capacity. It means we will need to have backup energy when solar radiation is less than 5 KWh/m^2/day where it will be immediately disconnected from the grid. In terms of global solar radiation, the assessment revealed that the maximum and minimum yearly global solar radiation is 7.451KWh/m^2/day and 3.15KWh/m^2/day. The idea was that since the global solar radiation value is calculated on the yearly basis, they are not very trustable in terms of accuracy as the monthly averaged values since the first referred to the peaks and the lowest figure occurred within the whole year. From the assessment, the study revealed that we are having much solar radiation during June, July, August, and some days of September. There is less solar radiation from February, March, April, and some days in May. It is from this concept of solar radiation unreliability, where this study was aimed to address this issue. Taking the monthly maximum and minimum values to be the inputs, the study has been put in place as a mitigation solution which is an integration of the energy storage system in grid-tied (GW Rwamagana). In this study, the energy storage system for the GW Rwamagana PV plant has been sized according to the gap we need to cover. The energy storage sizing process resulted in having the ability to generate the output voltage that equals the minimum possible voltage required for the converter to start serving the grid within 11 hours. The storage system consists of 2856 Lithium-ion batteries with 12 batteries connected in series to generate 562VDC and 238 batteries connected in parallel to meet the battery bank's current 4627A. Since the system will be charging all the time, we have an overgeneration, a charge controller was sized and integrated into the system to monitor the charging process that is to mean to avoid an overcharging and over-discharging the battery bank. A 48V300 Amph Lithium-Ion battery is preferred due to its characteristics. Lithium iron phosphate batteries give a number of advantages like enhanced discharge, charging, as well as efficiency. Longer life span is the main feature that gives this type of battery to be economically viable. The implementation of this study will help the new researchers in this field to have accurate information about solar radiation in these particular regions that will easy their researches as they will be having the input data to start on. For GW Rwamagana PV plant, having these kinds of data, it will speed up the plant upgrade process. For the community, this research will be a good input to design a solar related system and also data can be help in terms of economic growth very specifically in agriculturally based activities. Referring to the materials of in which the storage system is made of, the lithium-Ion batteries overcame measure challenges that would be brought by the acid-based storage batteries.

5 Conclusion and recommendations

This study mainly intended to focus on the assessment of solar radiation behavior where the GW Rwamagana PV plant is. The research was not only to concentrate on the place where the case study is but also the surroundings. That is to mean, society can benefit from the data and still rely on the results of this study to work on any other solar radiation activities investments within the same area. The owner of the PV plant understudy can still rely on the data to expand or to upgrade the existing plant either by implementing the storage features as well as adding more panels to raise the plant output. From the study, the GW Rwamagana PV plant can know when to produce more and when to store. Since solar radiation has proven to be a variable parameter in solar generation, the investors in this domain should be able to have a historical awareness and rely on this information during design. It will help in production efficiency as well as profit maximization.

6 References

[1] R. Sharma, V. Kumar, S. Sharma, V. Karthikeyan, and S. Kumaravel, “High Efficient Solar PV fed Grid Connected system,” Proc. 2018 IEEE Int. Conf. Power Electron. Drives Energy Syst. PEDES 2018, pp. 1–6, 2018, doi: 10.1109/PEDES.2018.8707850.

[2] M. Brenna, F. Foiadelli, M. Longo, and D. Zaninelli, “Energy Storage Control for Dispatching Photovoltaic Power,” IEEE Trans. Smart Grid, vol. 9, no. 4, pp. 2419–2428, 2018, doi: 10.1109/TSG.2016.2611999.

[3] N. Dhlamini and S. P. Daniel Chowdhury, “Solar Photovoltaic Generation and its Integration Impact on the Existing Power Grid,” 2018 IEEE PES/IAS PowerAfrica, PowerAfrica 2018, pp. 710–715, 2018, doi: 10.1109/PowerAfrica.2018.8521003.

[4] K. Alluhaybi, X. Chen, and I. Batarseh, “A grid connected photovoltaic microinverter with integrated battery,” Proc. IECON 2018 - 44th Annu. Conf. IEEE Ind. Electron. Soc., vol. 1, pp. 1597–1602, 2018, doi: 10.1109/IECON.2018.8591658.

[5] F. Matthey et al., “Cost-benefit analysis tool and control strategy selection for lithium-ion battery energy storage system,” IEEE Power Energy Soc. Gen. Meet., vol. 2015-Septe, 2015, doi: 10.1109/PESGM.2015.7286049.

[6] O. Vilppo, J. Markkula, P. Järventausta, S. Repo, and T. Hakala, “Cost-benefit analysis for using the Li-ion batteries in low-voltage network for decreasing the outage time experienced by customers,” CIRED - Open Access Proc. J., vol. 2017, no. 1, pp. 2201–2204, 2017, doi: 10.1049/oap-cired.2017.1006.

[7] M. Upasani and S. Patil, “Grid connected solar photovoltaic system with battery storage for energy management,” Proc. 2nd Int. Conf. Inven. Syst. Control. ICISC 2018, no. Icisc, pp. 438–443, 2018, doi: 10.1109/ICISC.2018.8399111.

[8] G. Yang and M. Chen, “Methodology for precisely estimating the generation of standalone photovoltaic system,” Proc. - 2009 Int. Conf. Environ. Sci. Inf. Appl. Technol. ESIAT 2009, vol. 1, no. 3, pp. 48–51, 2009, doi: 10.1109/ESIAT.2009.103.

[9] V. Kalkhambkar, R. Kumar, and R. Bhakar, “Optimal Sizing ofPV-Battery for Loss Reduction and (Nor),” IEEE Int. Conf. Recent Adv. i, vol. ICRAIE-201, 2014.

[10] V. Sok and T. Tayjasanant, “Determination of optimal siting and sizing of energy storage system in PV-connected distribution systems considering minimum energy losses,” ECTI-CON 2017 - 2017 14th Int. Conf. Electr. Eng. Comput. Telecommun. Inf. Technol., no. 2, pp. 451–

454, 2017, doi: 10.1109/ECTICon.2017.8096271.

[11] C. Museruka and A. Mutabazi, “Assessment of global solar radiation over Rwanda,” 2007 Int. Conf. Clean Electr. Power, ICCEP ’07, pp. 670–676, 2007, doi: 10.1109/ICCEP.2007.384312.

[12] “Estimation of global solar radiation in Rwanda.” .

[13] D. Saji, P. S. Babu, and K. Ilango, “SoC Estimation of Lithium Ion Battery Using Combined Coulomb Counting and Fuzzy Logic Method,” 2019 4th IEEE Int. Conf. Recent Trends Electron. Information, Commun. Technol. RTEICT 2019 - Proc., pp. 948–952, 2019, doi: 10.1109/RTEICT46194.2019.9016956.

[14] D. Dnkrx, A. Akhawayn, and U.-H. I. I. Ave, “Modeling and Dimensioning of Grid-Connected Photovoltaic Systems.”

[15] T. Horiba, “Lithium-ion battery systems,” Proc. IEEE, vol. 102, no. 6, pp. 1–12, 2014, doi: 10.1109/JPROC.2014.2319832.

[16] V. Karthigeyan, M. Aswin, L. Priyanka, K. N. Dileep Sailesh, and K. Palanisamy, “A comparative study of lithium ion (LFP) to lead acid (VRLA) battery for use in telecom power system,” 6th Int. Conf. Comput. Power, Energy, Inf. Commun. ICCPEIC 2017, vol. 2018-Janua, pp. 742–748, 2018, doi: 10.1109/ICCPEIC.2017.8290462.

[17] I. U. Khalil, M. Ahsan, I. Ullah, A. Adnan, N. Khan, and S. Nawaz, “SOC prediction of Lithium-Ion Battery using Extended Kalman Filter,” RAEE 2018 - Int. Symp. Recent Adv. Electr. Eng., pp. 1–5, 2018, doi: 10.1109/RAEE.2018.8706898.

[18] A. N. Al-shamani et al., “Design & Sizing of Stand-alone Solar Power Systems A house Iraq,” Recent Adv. Renew. Energy Sources, no. January, pp. 145–150, 2013, [Online]. Available: https://pdfs.semanticscholar.org/ac10/c05f8a9e233407132e0e86161f47c4840e98.pdf.

[19] S. Xie and F. Jin, “Low power consumption solar PV Charge Controller for telemetry system,” Proc. 2016 IEEE Adv. Inf. Manag. Commun. Electron. Autom. Control Conf. IMCEC 2016, pp. 1132–1136, 2017, doi: 10.1109/IMCEC.2016.7867388.

[20] L. Palma, “Design and Sizing of Energy Storage for Grid Connected PV Power Plants,” SPEEDAM 2018 - Proc. Int. Symp. Power Electron. Electr. Drives, Autom. Motion, no. fig 1, pp. 877–882, 2018, doi: 10.1109/SPEEDAM.2018.8445334.