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College of Science and Technology

Title of the Project: **FEASIBILITY STUDY OF HYBRID PV-HYDROPOWER COMPLEMENTARITY: CASE OF MUKUNGWA HPP**

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ABSTRACT

Photovoltaic-Hydro hybrid generation is a new multi-energy hybrid system combined with respective advantages, solar energy and hydropower**.** Stability and reliability are crucial parameters in power system operation. This research topic focuses on studying hybrid PV– Hydropower complementarity; the case of Mukungwa Hydropower Plant (HPP). This is a power station located in Rwanda's Northern Province. It was built in 1982 and has an installed capacity of 12 MW. Since its construction time, it has been operated as a reliable power plant. This is the plant that stabilizes the voltage for the Northern network. However, the power produced by the plant is reduced due to the high evaporation of water from the dam and hence, reduces the power generation during the summer season. This power reduction is estimated to be around 3 MW that is going to be covered by using the installation of a photovoltaic (PV) plant. It has been proposed in this study that a PV system can complement that power deficit during the high sunshine time. To validate the recommendation and check whether the system will be capable to supply the required power, the system is modeled and simulated using HOMER and PVSYST software. This study shows that the power reliability of Mukungwa HPP is improved by 5%. That is; the reliability is increased from 0.94 for a single generator to 0.99 after adding another generator in parallel. Economic analysis also shows a positive net present value (NPV) to prove the viability of the project.

Keywords: Hydropower power plant, PV power plant, hybrid system, power reliability

ACRONYMS

AC	Alternative Current
CO_2	Carbon Dioxide
COE	Cost of Energy
DC	Direct Current
DG	Distributional Generation
EAC	East African Community
GHG	Green House Gases
HOMER	Hybrid Optimization of Multiple Energy Resources
HPP	Hydropower plant
HRPGS	Hybrid Renewable Power Generation System
IPP	Independent Power Producer
ISS	International Space Station
MPPT	Maximum Power Point Tracking
MW	Mega-Watt
NPC	Net Present Cost
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
PV	Photovoltaic
REG	Rwanda Energy Group
RES	Renewable Energy Sources
SCADA	Supervisory Control and Data Acquisition
UR	University of Rwanda
USD	United State Dollars

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CHAPTER 1: INTRODUCTION

1.1 Background

Electricity plays a vital role in good living, industrial and business development. Thus, developing countries are making a concerted effort for achieving sustainable energy demand. Hydropower and photovoltaic (PV) are clean energy; that can help the provision of electricity to the people [1]. They require a waterfall and sun to produce electricity respectively. Such energy never ends, while other sources of energy will end as they are consumed [2]. The growing concern of global warming, depletion of petroleum reserves and the continuous increment of oil price have all led to the searching for alternative energy from renewable resources, this energy environmentally friendly, hence reduction of global warming [3].

Hydropower can quickly respond to the change of load when the demand increases suddenly. Its capacity depends on seasonal conditions. Also, it can be impacted by the reduction of water capacity during hot time. Rwanda is an eastern African country with too many sites with hydropower as a major source of electricity [4]. But during the strong sunshine time, the sites suffer from water reduction due to huge evaporation of the water from the dams, leading to unreliable energy supply. Therefore, a combination of two or more renewable energy resources may satisfy electricity demand and offer a reliable and consistent energy supply.

This case study is about Mukungwa Hydropower Plant (HPP). It is a power station located in Rwanda’s northern province. It was built in 1982 and has an installed capacity of 12 MW [6]. Since its construction time, it has been a reliable power plant. But as mentioned above, during the high sunshine time its electricity production is reduced. This energy reduction is to be mitigated using the installation of a PV plant; currently, when there is high load demand, a thermal plant is usually used to complement the hydropower plant but is harmful to human beings and the environment.

A hybrid PV hydropower generation system is proposed to mitigate this problem. Hybrid Renewable Power Generation System (HRPGS) is a system aimed at the production and utilization of electrical energy coming from more than one source, provided that at least one of them is renewable. Such a system often includes some kind of storage system to satisfy the demand during the periods in which renewable sources are not available. The proposed electricity storage system provides power to the load when the energy resource is not available or their capacity is unable to provide the required energy.

1.2 Statement of the Problem

The major electric energy source in Rwanda is hydropower. The amount of water collected by the dams varies depending on the seasonal variations and this has an impact on the reliability of the energy sources. During the heavy rain season, there is sufficient power. However, during the dry season, the amount of water capacity decreases significantly and hence the electricity being generated. This causes instability in the network and load shading. To overcome this problem, the diesel plants are switched on, which produces CO_2 emissions. This project aims at studying potential solutions to this critical problem.

1.3 Objectives

1.3.1 Major Objectives

The major objective of this project is to study the feasibility of complementary PV to improve the power reliability of hydropower plants.

1.3.2 The Specific Objective

The specific objectives of the research include:

- Study the level of power deficiency caused by the seasonal variation of rainfall.
- Design a PV system with which can supplement the hydro plant to meet the energy demand reliably.
- Model and simulate the hybrid system to verify that the system supplies the energy required reliably.
- Analyze financial costs for the PV plant.
- Analyze the performance of the designed system.
- Estimate the cost and analyze the economic feasibility of the system.

1.4 Scope of the study

An investigation will be carried out on a particular hydropower to assess its capacity to deliver a reliable power season with the variation of dam seasonal capacity. Power shortage during the dry season shall be determined and a hybrid solar PV shall be designed to compensate for the deficit. Components like PV module, inverter and charge controller shall be appropriately sized. The system will be simulated using PVSYST and HOMER software.

1.5 Expected Outcomes and Significance of the Study

1.5.1 Expected Outcome of the Study

From the studies, the use of solar power as backup power in the hot season shall be considered. The study shall appreciate the fact that solar power can be used to reduce the use of nonrenewable sources of energy, including coal, diesel, and natural gas which contribute to a huge percentage of the emission of greenhouse gases (GHG) leading to global warming. At the end of the study, a hybrid solar PV plant that is capable to produce power to compensate for the deficit in the hydropower plant during the dry season shall be designed. This will ensure a reliable and constant power supply from Mukungwa hydropower plant.

1.5.2 Significance of the Study

The combination of photovoltaic and hydro have the advantage that the two sources complement each other because the peak operating times for each system occur at different seasons of the year. The power generation of such a hybrid system can be more constant and reliable. The system provides a high level of energy security through a mix of generation methods, ensuring maximum supply reliability, security and constant generation regardless of the change in season. The system is dependable since it uses renewable energy sources that cannot be depleted and are environmentally friendly.

1.5.3 Organization of the Study

This thesis consists of six (6) main chapters which are divided into different sections as follows:

Chapter 1 introduces the topic to be discussed. It also contains the problem statement, objectives, scope, expected outcome and significance of the study.

Chapter 2 looks at the literature that is associated with the topic under study

Chapter 3 highlights the components of the PV Hydropower system

Chapter 4 discusses the data collection and description of the site, where we describe the site location and all data collected.

Chapter 5 shows the design and simulations, where we select the component to be used and the parameters to be controlled.

Chapter 6 discusses the conclusion and proposed the recommendations

CHAPTER 2: LITERATURE REVIEW

2.1 Hybrid System

2.1.1 Hybrid definition

A combination of different technologies based on renewable energies to produce power is known as a hybrid power system, it may work either with a backup source or itself [1]. Usually, hybrid systems are a combination of photovoltaic with wind turbines and/or generators running on diesel or biofuel or biogas and hydro. Some sources are considered intermittent others are available upon their need. Solar and hydropower are considered intermittent due to their availability, and their dependence on the climate condition. While other sources like Biogas, biomass and some other sources are considered continuous ones because their power production is steady. The resultant hybrid system could offer an optimal solution at a considerably lower cost. For example, in our case instead of using diesel as backup, due to high running costs. The new form of power generation (PV-hydro hybrid system) can modulate power out of the function of demand. A hybrid power system could be one of the solutions for complimenting hydropower. Using those renewable for power generation serves to decrease nonrenewable and imported fuel. The proposed hybrid combination could apply to other regions and elsewhere in the world especially where climate conditions are similar to our case study.

2.1.2 PV-Hydro Hybrid System

The hybrid system comprises PV and hydropower plants that are installed in the same location. During the dry season, there is a reduction in the volume of water flowing through the river. This reduces the capacity of water in the dam thus causing a decrease in the amount of power produced by the hydropower plant. To solve this problem, a PV plant can be built in parallel to the hydropower plant to compensate for the power deficit. During the dry seasons, the amount of solar irradiation tends to increase compared to the rainy season. As per the solar irradiance characteristics, much irradiance leads to much produced from solar. The output power from the inverter will be synchronized with the output of the generator from the hydropower side.

2.1.3 Advantages of hybrid systems

There are a lot of benefits of using a hybrid system based on renewable energies sources over a standalone system. Using the latter system could result in improved reliability and continuous power due to the ability of a hybrid system to provide backup power. The improved energy services, reduced emissions and noise pollution are benefits of hybrid systems since they adopt environment-friendly technology [2]. Those systems offer reduced costs due to the cost-effective way of generating electricity and lower maintenance cost associated with the use of renewable energies. They are efficient to use because renewable energy could be configured to comply with baseload [3].

2.2 Previous Works Done

Many researchers have ventured into stand-alone and hybrid power generation systems in Rwanda and all over the world. Different scholars have used different technologies and approaches to evaluate the various configurations of renewable energy resources, such as solar energy, hydropower and their hybrid configurations. From the studies, various results have been published as follows:

Gemma I, [4] studied a case study of a rural area in Rwanda entitled "Evaluation of a hybrid solar photovoltaic-bioenergy system for powering remote dwelling in Rwanda'' The presented work focuses on Kabasega Village in Gicumbi district, Northern Province of Rwanda. An off-grid hybrid system based on solar PV and biomass with a Fuel cell as a backup has been proposed. The objective was to evaluate the renewable energy resources in the chosen area to determine their potential in meeting the local energy needs. After that, a survey has been conducted to determine the village energy load demand. HOMER software has then been used to optimize a suitable system that meets the requirements. it has been found that, besides hydropower, the village has sizable energy potential in both solar and biomass resources. About 4.62 kWh/m^2 of average daily solar radiation and 2 tons per day of manure from cattle, goats, and poultry have been identified as the potential of chosen renewable energy resources. In this research, she did not show exactly the potentiality of poultry dropping that can be sufficient to generate bioenergy.

Jeannine U, [5] Studied a case study of rural area in Rwanda entitled "Design of Photovoltaic system for rural electrification in Rwanda'' The main goal of this project work was to show how a photovoltaic system can be used to solve the problem of electricity access in Kanazi, the village located in Nyamata sector of Bugesera District. Since the village is not connected to the grid, due to the high cost of transmission lines per km, photovoltaic technology such as solar home systems and standalone solar systems was proposed with a view of lower cost and high efficiency to generate electricity for households and public service applications. Due to climatic conditions, Nyamata sector receives abundant amounts of solar irradiation all year around. Since solar energy is available only during the day, it is important to use it with energy storage devices like batteries to supply the load during the night to ensure a self-sufficient system. this project work provides a basis and framework for the evaluation of this solution not only in Bugesera, but also in other parts of the country where the sunshine is relatively intensive and based on the results from simulation, an additional step of grid connection during the rainy season can also be embraced. Therefore, the village system of 10 kW is selected to be the best since solar home systems are limited to household applications and the availability of supply is low. In this research, she did not show us an alternative source that can be explored, in the time the solar fail to supply energy.

Jean De Dieu N. et al [6] presented a paper titled “Key technology development needs and applicability analysis of renewable energy hybrid technologies in off-grid areas for the Rwanda power sector’’ The hybrid systems simulation and optimization were obtained using HOMER (hybrid optimization model for electric renewables) software. The input data obtained from the National Aeronautics and Space Administration (NASA) for solar, wind and hydro resources were from real-time field data for the selected study sites. The simulation results indicate hydro/ solar/battery hybrid is the most cost-effective and environmentally viable alternative for off-grid rural electrification because of low net present cost (NPC) and least greenhouse gas emissions. The proposed hybrid for combination could apply to other rural areas in the region and elsewhere in the world, especially where climate conditions are similar. They should show the sustainability of using the battery as storage which needs to be replaced every 5 years. this increases the future cost.

Nisingizwe Emmanuel et al [7] presented a case study for rural electrification in Rwanda entitled “Design of solar – Wind hybrid system for rural electrification in Rwanda”. This project aimed to study the feasibility of a Wind-PV hybrid system for local electricity production to power rural communities in Kayonza District where the strongest wind speed was found in the country by using HOMER software. The main objective was to develop a hybrid system cost competitively to supply energy for remote villages for a model community of 200 households with one primary, secondary school, one milling house, one health center and one government building which is used as an office. This study intended to promote an efficient and cost-competitive system configuration of a hybrid power system to improve the lives of the rural community not yet connected to the national grid. It concluded that renewable energy sources and/or their hybrid configuration are cost-competitive although the huge capital investment of the renewable energy resources is the major limitation. However, from the social point of view and improvement of the life of the people not connected from the national grid, the cost is not a significant matter and cannot be rejected. However, this study does not indicate how the high initial capital cost can be reduced or replaced by locally available alternative energy sources.

CHAPTER 3: COMPONENTS OF PV-HYDROPOWER HYBRID SYSTEM

3.1 Hydroelectric power plant

Hydroelectric power (often called hydropower) is considered to be a green energy source. With hydropower, the energy in falling water is converted into electricity without "using up" the water. Generation of electricity by hydropower (potential energy in stored water) is one of the cleanest methods of producing electric power. In 2012, hydroelectric power plants contributed about 16% of the total electricity generation of the world. Hydroelectricity is the most widely used form of renewable energy. It is a flexible source of electricity and also the cost of electricity generation is relatively low. This article talks about the layout, basic components and working of a hydroelectric power station [8]

Hydropower generates electricity by using the potential energy difference of water at different heights. The output of the hydropower station is determined by power discharge, water head and energy loss; which depends on the efficiency of the hydro-generator

$$Ph = 9.81\eta QH \tag{3.1}$$

Where Q is the water flow volume per unit of time in the measured profile through the turbine inlet, H is the net water head; η is the hydropower efficiency.

Hydropower is one of the reliable and promising sources of electricity on earth. It is produced by energy provided by moving or falling water. Research has proved that the cost of this electricity remains constant over the year. Because of the many advantages, most of the countries now have hydropower as the main source of electricity. Hydropower is green energy therefore, there are no air or water pollutants and greenhouse gases like carbon dioxide are not produced which makes it environment-friendly.

3.2. Basic Components Hydropower Plant (HPP)

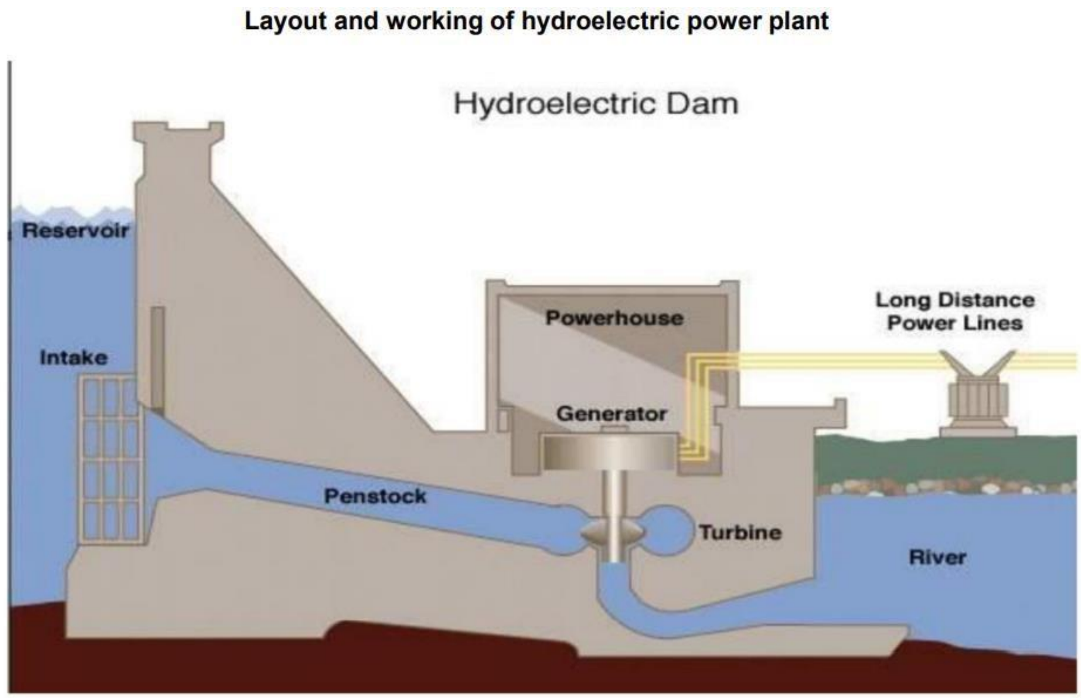

Figure 3. 1 Layout of the hydropower plant [8].

Dam and Reservoir: The dam is constructed on a large river in hilly areas to ensure sufficient water storage at height. The dam forms a large reservoir behind it. The height of the water level (called as water head) in the reservoir determines how much potential energy is stored in it [8].

Control Gate: Water from the reservoir is allowed to flow through the penstock to the turbine. The amount of water that is to be released in the penstock can be controlled by a control gate. When the control gate is fully opened, the maximum amount of water is released through the penstock.

Penstock: A penstock is a huge steel pipe that carries water from the reservoir to the turbine. The potential energy of the water is converted into kinetic energy as it flows down through the penstock due to gravity.

Water Turbine: Water from the penstock is taken into the water turbine. The turbine is mechanically coupled to an electric generator. The kinetic energy of the water drives the turbine and consequently, the generator gets driven. Two main types of water turbine are counted; (i) Impulse turbine and (ii) Reaction turbine. Impulse turbines are used for large heads and reaction turbines are used for low and medium heads [8].

Generator: A generator is mounted in the powerhouse and it is mechanically coupled to the turbine shaft. When the turbine blades are rotated, it drives the generator; hence the electricity is generated which is then stepped up with the help of a transformer for the transmission purpose.

Surge Tank: Surge tanks are usually provided in high or medium head power plants when considerably long penstock is required. A surge tank is a small reservoir or tank which is open at the top. It is fitted between the reservoir and the powerhouse [8]. The water level in the surge tank rises or falls to reduce the pressure swings in the penstock. When there is a sudden reduction in load on the turbine, the governor closes the gates of the turbine to reduce the water flow. This causes pressure to increase abnormally in the penstock. This is prevented by using a surge tank, in which the water level rises to reduce the pressure. On the other hand, the surge tank provides excess water needed when the gates are suddenly opened to meet the increased load demand.

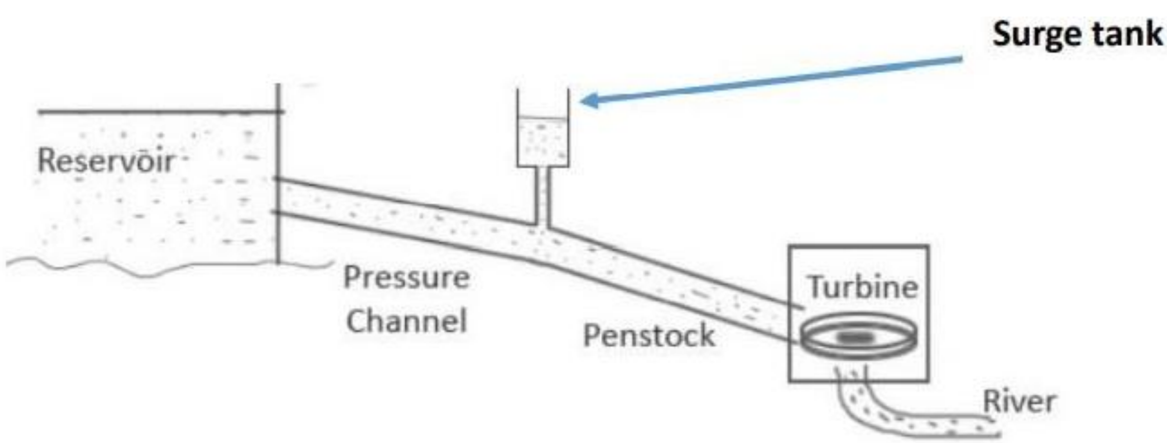

Figure 3. 2 Location of the surge tank.

3.2.1 Types of Hydro-power plants

- Conventional plants: Conventional plants use potential energy from dammed water. The energy extracted depends on the volume and head of the water. The difference between the height of the water level in the reservoir and the water outflow level is called as water head.

- Pumped storage plant: In the pumped storage plant, a second reservoir is constructed near the water outflow from the turbine. When the electricity demand is low, the water from the lower reservoir is pumped into the upper (main) reservoir. This is to ensure a sufficient amount of water available in the main reservoir to fulfill the peak loads.

-Run-of-river plant: In this type of facility, no dam is constructed and, hence, a reservoir is absent. A portion of the river is diverted through a penstock or canal to the turbine. Thus, only the water flowing from the river is available for generation. And due to this absence of a reservoir, any oversupply of water is passed unused.

Advantages and disadvantages of hydroelectric power plant

Advantages of a hydroelectric power plant.

- No fuel is required as potential energy is stored water is used for electricity generation.
- Neat and clean source of energy.
- Very small running charges - as water is available free of cost.
- Comparatively less maintenance is required and has longer life.
- Serves other purposes too, such as irrigation, fishing, municipal water.

Disadvantages

- Very high capital cost due to construction of the dam.
- High cost of transmission as hydro plants are located in hilly areas which are quite away from the consumers.

3.2.2 Hydropower in Rwanda

Rwanda's major Rivers have proven 333 potential sites for Micro-hydropower countrywide. Opportunities exist in Micro and Small Hydropower projects and shared regional hydropower projects with East African Community (EAC) Partners. A couple of micro and mini small Hydropower Projects are currently under construction. The largest domestic hydropower project is Nyabarongo I, with an installed capacity of 28 MW. Some shared hydropower projects with neighboring countries are also underway, including a 145 MW project shared by Burundi, DRC and Rwanda; and an 80 MW project to be jointly developed by Tanzania, Burundi and Rwanda.

Among them, only 21 hydropower plants are grid-connected. They include national and shared regional projects (Rusizi I and II HPPs). Hydropower makes up approximately 47% of the total installed capacity. Hydropower plants are publicly owned and operated, leased to private companies, or privately owned by Independent Power Producer (IPP) [9].

3.2.3 Mini and Small Hydropower

Currently, 11 micro hydropower plants MW exist in Rwanda as isolated networks. These plants were originally developed by the GoR, and handed over to private sector management to increase the private sector contribution to energy generation. GoR has recently leased out these sites to a private investor to better operate, upgrade and connect them to the grid. There are also Pico-hydropower plants in the range of 1-10 kW which are either publicly owned or operated by the local communities or entirely private.

By December 2016, 7 privately developed hydropower plants with a total capacity of 16 MW were under different phases of construction, with commercial operation dates (COD) that were planned in 2019. Feasibility studies conducted by Rwanda Energy Group indicated potential in micro-hydropower generation in over 40 smaller sites [9].

3.2.4 Medium Hydropower

Nyabarongo II (43.5MW) is a multipurpose project expected to cater for water supply, irrigation as well as electrical power generation. The project is also envisaged to mitigate the perpetual flooding downstream of the Nyabarongo River that has proved to be hazardous in recent years [9]. The project is fully funded by the Government of Rwanda is expected to start end of 2019 and is expected to be completed in 2025. The project consists of a 48 m high concrete gravity dam with a crest of 228m and a surface power station with 2*8.5 MW Kaplan turbines just situated at the dam toe.

Rusizi III (145MW) supported by World Bank, EU, AfDB among others with an expected investment capital of $450 million and completion date in 2024. The project is being developed under the CEPGL umbrella for Rwanda, Burundi and DRC. Rusizi III hydropower project is planned to generate 145MW and the power output is shared among the three partner states with Rwanda getting 48.3MW and the rest is shared between Burundi and DRC [9]. The project consists of a 105 m long dam crest whose height is 20.5 m, 2.28 km Headrace Tunnel and a surface power station with 3*50 MW Francis Units.

Rusumo Falls Hydro-Electric Power (80MW) falls. The construction of the project started in 2017 and is planned to be completed end of 2020. The project is being developed under the NELSAP umbrella for Rwanda, Burundi and Tanzania funded by the World Bank.

Rusumo falls Hydropower Project is planned to generate 80 MW and the power output will be shared equally by three countries. The project consists of a concrete dam with a crest length of 150 m, a Headrace Tunnel of 460 m and a surface power station with 3*30MW Kaplan turbines [9].

3.3 Photovoltaic system

Solar cells are made of semiconductor materials (usually silicon), which are specially treated to form an electric field, positive on one side (backside) and negative on the other (towards the sun). When solar energy (photons) hits the solar cell, electrons are knocked loose from the atoms in the semiconductor material, creating electron-hole pairs. If electrical conductors are then attached to the positive and negative sides, forming an electrical circuit, the electrons are captured in the form of an electric current Iph (photocurrent) [10].

3.3.1 Solar cell model

During darkness, the solar cell is not an active device; it works as a diode, i.e. a p-n junction. It produces neither a current nor a voltage. However, if it is connected to an external supply (large voltage) it generates a current ID, called diode current or dark current.

A solar cell is usually represented by an electrical equivalent one-diode model. as shown in Figure below.

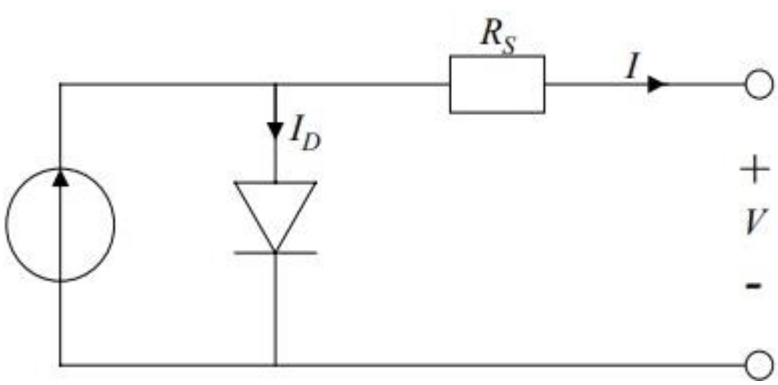

Figure 3. 3 Model for a single solar cell.

The model contains a current source Iph, one diode and a series resistance RS, which represents the resistance inside each cell and in the connection between the cells. The net current is the difference between the photocurrent Iph and the normal diode current I_D:

$$I = I_{ph} - I_D = I_{ph} - I_O \left(exp \frac{e(V+IRS)}{mkTc} - 1 \right) \quad (3.2)$$

Where ***m*** is idealizing factor, ***k*** is Boltzmann's gas constant, ***Tc*** is the absolute temperature of the cell, ***e*** is the electronic charge and ***V*** is the voltage imposed across the cell. $\boldsymbol{I_o}$ is the dark saturation current and it is strongly depending on the temperature in the cell.

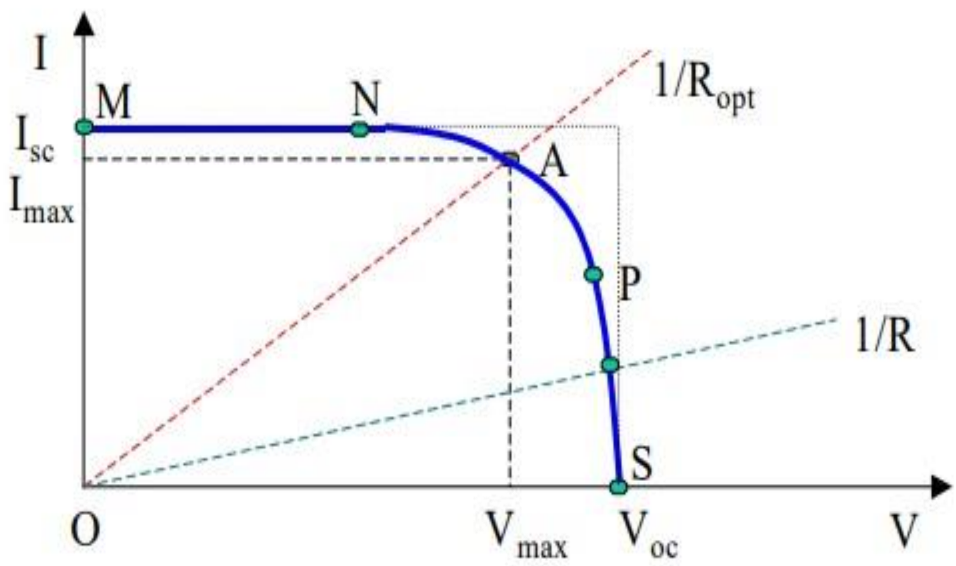

Figure 3. 4 The I-V characteristic of the solar cell for a certain ambient irradiation Ga and a certain fixed cell temperature Tc [11].

In the representation of I-V characteristics, a sign convention is used, which takes as positive the current generated by the cell when the sun is shining and a positive voltage is applied on the cell's terminals.

If the cell's terminals are connected to a variable resistance R, the operating point is determined by the intersection of the I-V characteristic of the solar cell with the load I-V characteristic - see Figure 3.4 For a resistive load, the load characteristic is a straight line with a slope $I/V = 1/R$. It should be pointed out that the power delivered to the load depends on the value of the resistance only. However, if the load R is small, the cell operates in the region MN of the curve, where the cell behaves as a constant current source, almost equal to the short circuit current. On the other hand, if the load R is large, the cell operates on the region PS of the curve, where the cell behaves more like a constant voltage source, almost equal to the open-circuit voltage.

A real solar cell can be characterized by the following fundamental parameters, which are also sketched in Figure 3.4

(a) Short circuit current: $scph\,I = I$. It is the greatest value of the current generated by a cell. It is produced under short circuit conditions: $V = 0$.

(b) 0pen circuit voltage corresponds to the voltage drop across the diode (p-n junction), when it is traversed by the photocurrent Iph (namely $ID = Iph$), namely when the generated current is I = 0. It reflects the voltage of the cell in the night and it can be mathematically expressed as:

$$Voc = \frac{mkTC}{e} \times ln(\frac{Iph}{I0}) = Vt \times ln(\frac{Iph}{I0}) \quad (3.3)$$

Where $Voc = \frac{mkTC}{e}$ is known as thermal voltage and Tc is the absolute cell temperature

(c) Maximum power point is the operating point A (V_{max}, I_{max}) in Figure 3.4, at which the power dissipated in the resistive load is maximum:

$$P_{max} = I_{max} \times V_{max} \quad (3.4)$$

(d) Maximum efficiency is the ratio between the maximum power and the incident light power.

$$\eta = \frac{P_{max}}{Pin} = \frac{I_{max} \times V_{max}}{AGa} \quad (3.5)$$

Where Ga is the ambient irradiation and A is the cell area

(e) Fill factor is the ratio of the maximum power that can be delivered to the load and the product of Isc and Voc

(e) Fill factor is the ratio of the maximum power that can be delivered to the load and the product of Isc and Voc

$$FF = \frac{P_{max}}{Voc \times Isc} = \frac{I_{max} \times V_{max}}{Voc \times Isc} \quad (3.6)$$

The fill factor is a measure of the real I-V characteristic. Its value is higher than 0.7 for good cells. The fill factor diminishes as the cell temperature is increased.

For practical use, solar cells can be electrically connected in different ways: series or parallel. Figure 3.5 presents how the I-V curve is modified in the case when two identical cells are connected in series and in parallel [12].

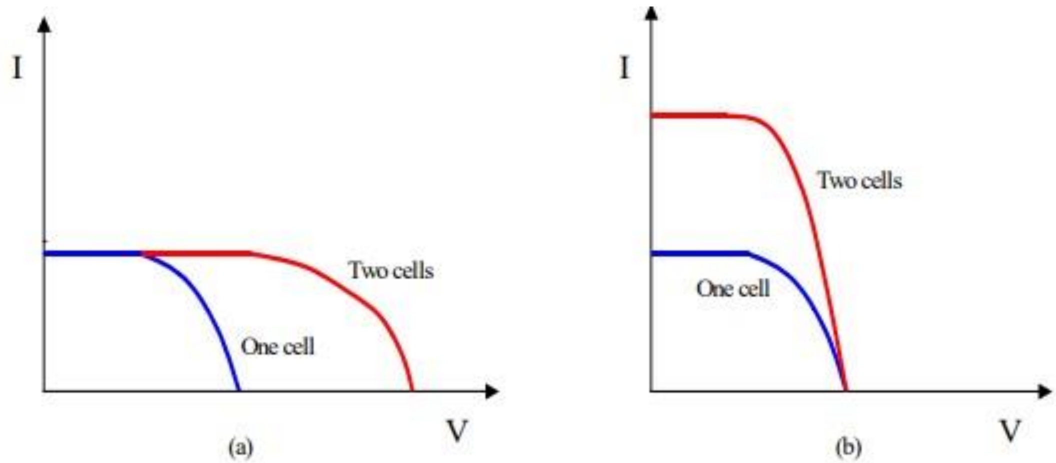

Figure 3. 5 Series (a) and parallel (b) connection of identical cells [11].

It is seen that I-V characteristics of series interconnected cells can be found by adding, for each current, the different voltages of the individual cells. On the other hand, for parallel cells, the currents of the individual cells must be added at each voltage to find the overall I-V curve [11].

3.3.2 Module model

Cells are normally grouped into different "modules", which are encapsulated with various materials to protect the cells and the electrical connectors from the environment. The manufacturers supply PV cells in modules, consisting of NPM parallel branches, each with NSM solar cells in series, as shown in Figure 3.6.

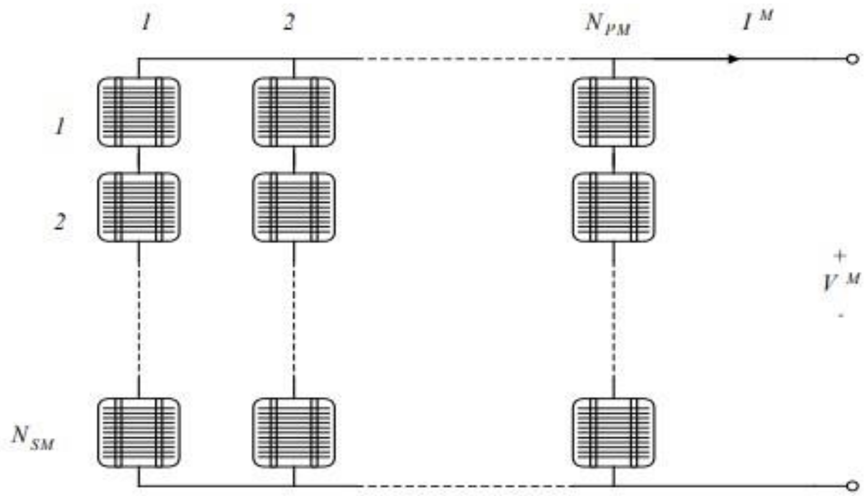

Figure 3. 6 Grouping of cells for PV Module [11].

The PV module consists of NPM parallel branches, each of NSM solar cells in series. To have a clear specification of which element (cell or module) the parameters in the mathematical model are regarding, the following notation is used from now on: the parameters with superscript" M" are referring to the PV module, while the parameters with superscript "C" are referring to the solar cell. Thus, the applied voltage at the module's terminals is denoted by V M, while the total generated current by the module is denoted by IM [11], [12]. A model for the PV module is obtained by replacing each cell in Figure 3.6 above, with the equivalent diagram.

3.3.3 Solar panel positioning angles

Tilt Angle

Tilt angle is defined as the slope angle at which solar panels are mounted to face the sun. Sun's position changes according to the earth's direction every day, so the mounting angles of panels also keep on changing. Generally, the tilt angle is taken to be equal to the latitude of the considered location. An optimum value of tilt angle is required to get the maximum amount of solar energy onto the panels.

Azimuth Angle

Azimuth angle defines the direction of the sun. It is taken as zero as the panels are mounted facing south in the northern hemisphere

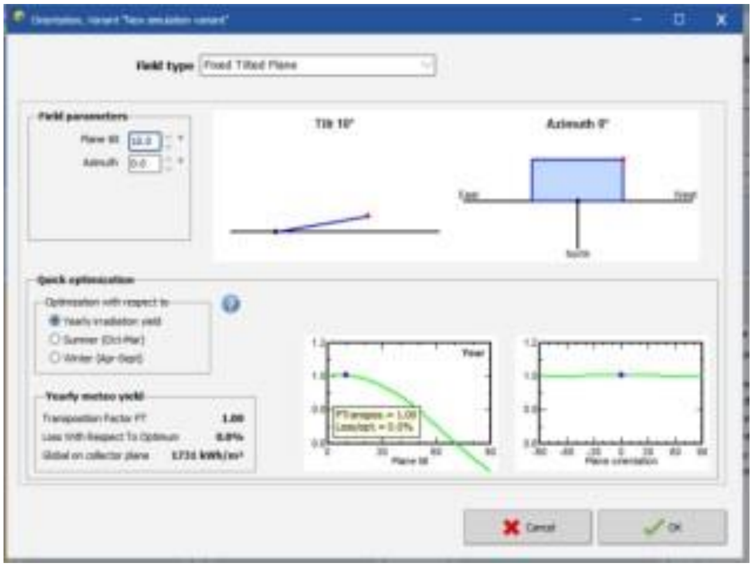

Figure 3. 7 Tilt and Azimuth Angle.

3.3.4 Types of Solar Cells

Crystalline Silicon is the leading material for solar cells. It is relatively expensive.

Monocrystalline cells are made from electronic-grade silicon and have efficiencies up to 25 %.

Polycrystalline cells are cheaper and made from solar grade silicon but their efficiency is about 15 %.

Amorphous Silicon Solar Cells that are used for many years to manufacture cells to power watches, calculators etc. It is a solid material with no regular crystalline structure. Cell efficiencies range from 5% to 10%. Manufacturing yield is a problem and cells suffer from degradation when exposed to the sun. Types of Solar Cells

Thin Film Solar Cells are made by depositing active PV material such as amorphous silicon onto glass together with necessary current collecting contacts. Cheaper than other methods which require semiconductor wafers. Suitable for making cells with a larger area and high current carrying capability. Efficiencies range from 11% to 14%.

Organic PV Solar Cells are currently undergoing intensive research. Devices can be fabricated using a printing process from single or double-layer organic polymer films sandwiched between a pair of electrodes. Manufacturing does not involve the high energy consumption associated with crystalline semiconductors, bringing the possibility of high volume, low-cost products printed onto flexible films. The conversion efficiencies are rather low at around 12% but this is expected to be improved.

Multi-layer (Tandem) Solar Cells lead to better conversion efficiencies by using multiple layers of different semiconductor materials, optimized for different wavelengths, in a single device. This can raise the theoretical efficiency limit, currently about 30% for a single-junction device, to about 45% for a three junction cell. The efficiencies of over 33% have already been achieved in practical devices.

3.3.5 Advantages of photovoltaic technology

Compare to other technologies, the PV system presents several advantages including being reliable. That means capable of working even in harsh conditions, its modules are guaranteed for 25 years with production even after that period. This technology requires low maintenance cost mostly only periodic and occasional maintenance are required [13]. Additionally, the system is a free fuel use in power production and is environmentally friendly with less sound pollution only from pumped and tracked systems. To increase the power output, PV modules can be added due to their modularity. Last but not least, the system is independent as it can be a stand-alone system with no grid-tied components.

3.4 Solar Energy in Rwanda

3.4.1 Solar radiation in Rwanda

Rwanda is geographically around the equator and has sufficient sunshine with an estimated average daily global solar irradiation on the tilted surface of 5.2 kWh per m^2 [14]. From 4.8 kWh per m^2 to 5.8 kWh per m^2 per day has been recognized as the long-term range of monthly average global irradiation and that indicates the sufficient and good potential for solar energy.

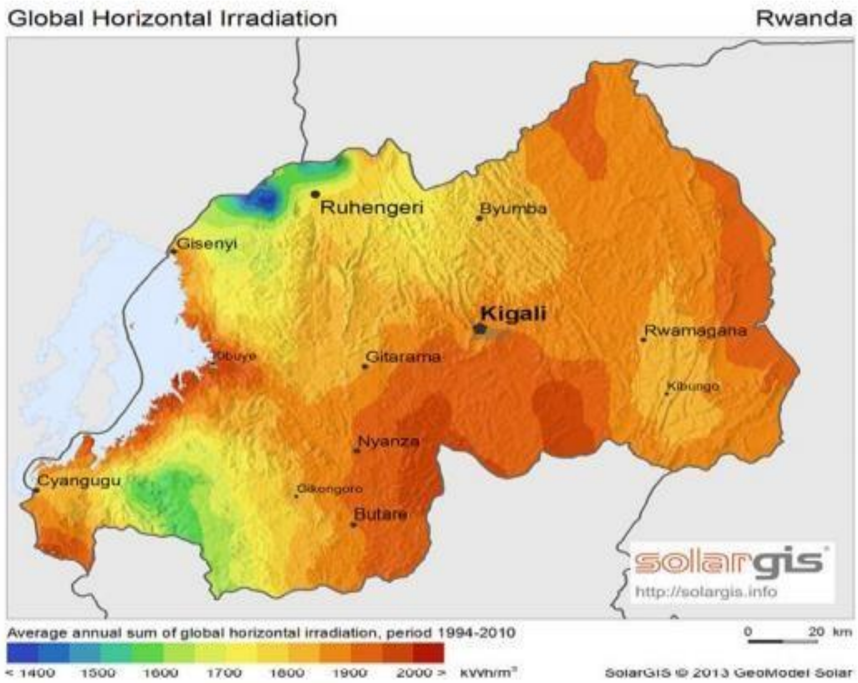

Figure 3. 8 Rwanda global horizontal irradiation [15], [16].

With that sufficient potential of solar radiation in Rwanda, there is significant solar energy development, and two technologies solar PV and the solar water heater are currently taking place. The former is more used to generate electricity either as on grid-connected or off-grid to supply communities in remote areas where government buildings, schools, and health institutions are more beneficial. The government, donors and private sectors are all contributing to that development. In Rwanda, in Rwamagana district Agahozo - Shalom Youth Village, there is an 8.5 MW solar power plant and is the first utility-scale farm in east Africa. This plant uses 28.360 PV panels and has 20 hectares of land. It produces 6% of the total electricity supply of the country[16]. Rwanda's Total on-grid installed solar energy is 12.08 MW. Households far away from the planned national grid coverage are encouraged to use standalone solar photovoltaic (PVs) to reduce the cost of access to electricity. The Rural Electrification Strategy in Rwanda approved in June 2016 outlines strategies through which Rwanda's households could "have access to electricity through the most cost-effective means by developing programs that will facilitate both the end-users to access less costly technologies and increase private sector participation in the provision of these solutions. The Energy sector strategic plan underscores the universal access to electricity by 2024 with 48% of the households connected through off-grid power systems.

3.4.2 Existing Projects

Mount Jali in Kigali 250KWp Solar Plant. In 2006, the government of Rwanda signed an MoU with German state Rhineland-Palatinate to construct, own and operate a 250 kWp grid-connected solar plant and commissioning was done in 2007. It was funded by the German municipal power company Stadtwerke Mainz and installed by July 2008. The plant was constructed on the top of Mount Jali in Kigali City. Since its commissioning date, the plant has been operating successfully.

Rwamagana Solar Power Plant (8.3 MW). The US23.7 million Rwamagana solar plant was built in collaboration with Gigawatt Global and is located near AgahozoSharlom Youth Village in Rwamagana District. The plant is the first utility-scale solar power plant in East Africa, was commissioned in February 2015.

Nasho Solar (3.3 MW) power plant. The project was established and commissioned in 2017 to 3-megawatt solar energy to power up the irrigation system and the surplus is used to light up homes in the area. The project was funded by the Howard G Buffett Foundation in collaboration with the Ministry of Agriculture [16].

3.5 Solar Inverter and MPPT System

A solar inverter is needed by the PV system in case of AC loads to convert the generated DC voltage into AC voltage as required by different AC loads. Also for ensuring the best performance of the PV modules, an MPPT system is important and since the technology has improved this system is usually incorporated with solar inverters in most grid-connected system PV systems. The efficiency of an inverter varies per load demand and their efficiency curve is usually provided by the manufacture. An inverter provides a factor of compatibility, but its use can reduce the array's available electricity if it is not suitably designed to match the electrical load [4]. Essentially, an inverter is a set of automatic switches that provide polarity reversals from the solar array shown in Figure 3.8. It will be in interconnection with the grid, some conditions should be followed to follow the aspect of synchronization [7].

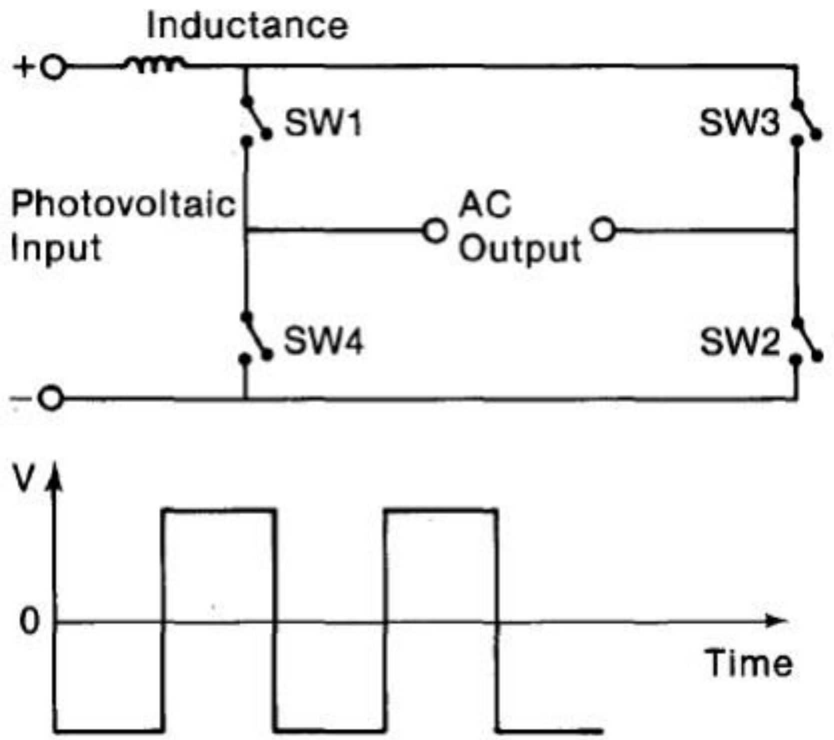

Figure 3. 9 Inverter's circuit diagram with different electronic switching circuits [17].

In the system illustrated above, when switches 1 and 2 are closed, the AC output is positive at the left terminal. When switches 3 and 4 are closed the positive AC terminal is on the right. Opening and closing, alternately; the switches in pairs (1/2 and 3/4) produce square waveform as shown in the bottom portion of the illustration [17].

3.6 Rwanda electrification profile

Rwanda is endowed with various energy resources, which include renewable energy like hydropower, geothermal, biomass (firewood and charcoal) and solar. It has also conventional energy like methane gas and diesel generators. All the above lead to an electrification rate of 63% in 2021 [18], while the targeted rate was 75% by 2020, compared to 23% in 2015. This target was expected to reduce the use of wood from 90% to 50% for national consumption [19], [20].

3.6.1 The State of the Power Sector in Rwanda

The Government of Rwanda through its power sector has very ambitious targets to achieve 512 MW installed power generation capacity, from its current 235.6 MW power generations and have universal access (100%) by 2023/24. It is also determined to achieve 52% on-grid connections and 48% off-grid connections by 2023/24 [20].

3.7 Reliability definition

Reliability can be defined as the probability that a device, component system, or equipment will function under specified conditions for a given period.

$$R = e^{-\lambda t} \tag{3.7}$$

Where $\boldsymbol{\lambda}$ is the failure rate and t is the period of operation.

3.7.1 Reliability of electric power system

Since the industrial evolution of man’s demand for and consumption of electric energy has increased steadily. However, to meet the ever-increasing demand for electric energy very complex power systems have been built to satisfy the demand [21]. This vast enterprise of supplying electrical energy present many engineering problems that causes a variety of challenges. Thus, the successful operation of any power system depends largely on the engineer's ability and capability to provide reliable and uninterrupted service to the loads. The reliability of the power supply entails that the loads must be fed at a constant voltage and frequency at all times. Practically, the load and frequency must be held within close tolerance so that the consumer’s equipment and appliances may operate satisfactorily [22], [21].

Another method of achieving reliability is to indulge in system reliability planning. This will ensure proper evaluation of the entire system so that overall reliability measures can be taken. For accurate reliability, each basic branch of the power system (i.e. generation, transmission and distribution) should be separately measured [21]. In the planning of a power system, reliability improvement should be considered. And this could be achieved by considering better components and provision of redundancy.

In a generation, redundancy could be achieved by using multiple generators in parallel and reconfiguring the structure. The redundancy in transmission could be achieved by making the ties between stations and load centers stronger [21]. For the distribution system, the use of a better scheme and duplication of certain components ensure redundancy in the system.

3.7.2 Indices reliability

(1) System Average Interruption Duration Index (SAIDI) [23]: This is designed to provide information about the average time, the customers are interrupted. This system is commonly referred to as consumer minutes of interruption or customer hours. SAIDI indicates the sum of the restoration time for each interruption event times, the number of interrupted customers for each interruption event divided by the total number of customers.

$$SAIDI = \frac{Sum\ od\ customer\ interruption\ durations}{Total\ number\ of\ customers\ served} \quad (3.8)$$

(2) Customer Average Interruption Duration Index (CAIDI): This is the sum of customer interruption duration divided by the total number of customer interruptions. It is the average time need to restore service to average interrupted customers [23].

$$CAIDI = \frac{Sum\ of\ customer\ interruption\ durations}{Total\ number\ of\ customer's\ interruption} \quad (3.9)$$

(3) System Average Interruption Frequency Index (SAIFI) [23]: This is the average frequency per customer who was interrupted with a specified time. Mathematically, it is the total number of interrupted customers divided by the total number of customers utilizing the electricity.

$$SAIFI = \frac{Total\ number\ of\ customer\ interruptions}{Total\ number\ of\ customer\ served} \quad (3.10)$$

3.7.3 Elements of reliability

Failure: the failure of a component, unit or equipment is the inability of a component to perform its intended function at a particular time under specified operating conditions. A failure could be due to loss of output, change in output, deviation from specification value. Adequate reliability depends upon the equipment failure.

Failure Rate: the equipment failure of a unit. The component is the number of failures per unit time. It is denoted by λ. Also, the equipment is the number of unit failures divided by unit available during which they occur. It is often quoted as the percentage of failures in a given time.

$$\boldsymbol{Failure\ rate} = \frac{Number\ of\ failures}{Total\ operating\ times\ of\ units} \quad (3.11)$$

Repair Rate: This is the number of repairs per unit time. Its symbol is μ.

Outage: This is the state of the device when it is not operating due to voluntary or involuntary action outage may occur due to interruption. This is an outage breakdown or isolation of subsystem.

Forced Outage: Due to emergency conditions, it can occur due to human error, improper operation or automatic trips.

Scheduled Outage: Occurs due to deliberate action, for example during maintenance, repairs and services.

Momentary Outage: This is an outage that occurs due to closing and clearing temporary faults

3.7.4 Reliability of common system configurations

A system as noted earlier is composed of components that work together to form a configuration and execute a goal. The following are possible system configurations.

(a) Series System: A system in which all the components are arranged in series. A series system fails whenever one of the components fails. If a serried system consists of reliability R1. R2 - R3. R4

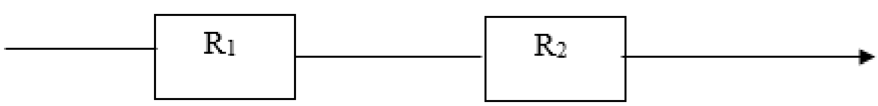

Figure 3. 10 Series System.

Rn. The system reliability Rs by

$$Rs = R1.R2.R3.R4 \ \ldots\ldots...Rn \qquad (3.12)$$

$$Rs = e^{-\lambda}1^t \times e^{-\lambda}2^t \times e^{-\lambda}3^t \times e^{-\lambda}4^t \times \ldots\ldots\ldots\ldots\ldots.\times e^{-\lambda}n^t \qquad (3.13)$$

(b) Parallel System: Is a system in which constituent components are connected in parallel. A parallel system fails when all the components have failed. In a parallel system, the system reliability is calculated by Equation (3.14).

$$RS = 1 - e^{-\lambda_1 t} \tag{3.14}$$

$$R_{tot} = 1 - (1 - R_A) * (1 - R_B) \tag{3.15}$$

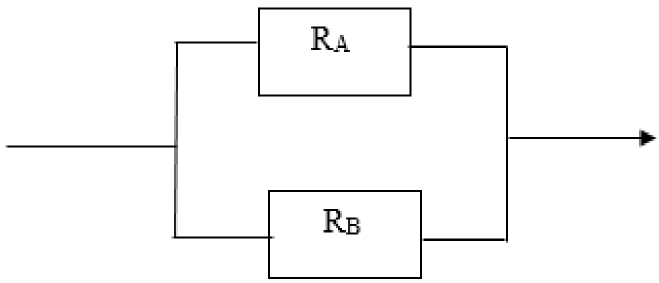

Figure 3. 11 Parallel system.

(c) Parallel Series System / Series-Parallel System: A system that consists of components arranged in parallel and series combination. Their failure pattern is complex depending on the arrangement of the components of the system.

Let us assume that we have two generators of failure rate (λ) equal 0.0022/h and 0.0032/h and repair rate (µ) equal to 0.02/h and 0.04/h respectively. Both generators operate 24hrs/day. We can calculate the reliability of the system.

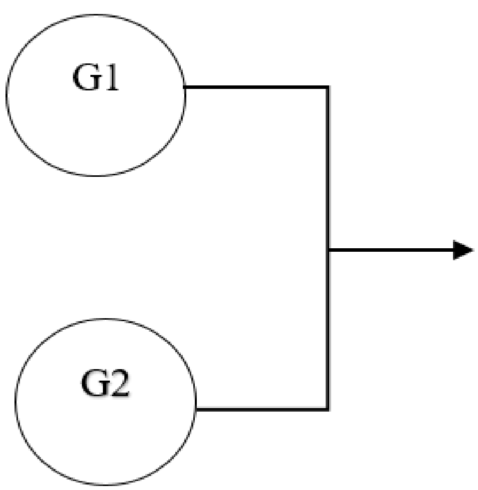

Figure 3. 12 Parallel Power Generators.

Failure rate (λ) for G_1=0.0022/h

Failure rate (λ) for G2=0.0032/h

The individual Reliabilities and that of the whole system (R_{tot})are calculated using Equations (3.13) and (3.15) respectively as follows:

Reliability of $G_1R_1 = e^{-\lambda_1 t} = e^{-0.0022*24} = 0.94$

Reliability of $G_2R_2 = e^{-\lambda_2 t} = e^{-0.0032*24} = 0.93$

The reliability of the system is equal = Rtot = 1- (1- R_1) * (1 –R_2) =1-(1-0.94) *(1-0.93) =0.99

From this scenario, it is seen that the reliability increase when two generators are in parallel.

3.8 Introduction to HOMER software

The word HOMER stands for Hybrid Optimization Model for Electricity Renewables. It is a free software application developed by the National Renewable Energy Laboratory in the United States (NREL). It was developed in 1993 to understand the tradeoffs between different energy production configurations for the use of the internal Department of Energy (DOE). The use of this software is to design and evaluate the options for both off-grid and grid-connected power systems for remote areas, stand-alone and distributed generation applications both technically and financially [24], [25]. HOMER simulates different configurations of renewable energy sources (RES) and scales them based on net present cost which is the installation and operating total cost of the system over its lifetime [25], [24].

3.8.1 HOMER working principle

In the year, each of the 8760 hours, HOMER simulates the operation of a system by making energy balance calculations. It performs these energy balance calculations for each system configuration that the designer or the user wants to consider. After that HOMER helps to determine the feasibility of a configuration to meet the electric demand under the specified conditions lastly but not least over the project’s lifetime, it estimates the cost of installing and operating the system [24].

3.8.2 Advantages and disadvantages of HOMER

Table 3. 1 Advantage and Disadvantage of HOMER Software.

Advantages	Disadvantages
Homer stimulates a list of real technologies as a catalog of available technologies and components.	Quality of input data is needed(sources)
HOMER provides detailed results for analysis and evaluation	Detailed input data and time are needed
It determines the possible combinations of a list of different technologies and their size	Experienced criteria are needed to converge to the good solutions
It is fast to run many combinations	HOMER will not guess the missing key values or sizes
You can learn from the results and optimize	You can lose yourself if you don't set the adequate questions

3.9 Introduction to PVsyst Software

PVsyst is a photovoltaic design and simulation program. It is designed to be used by architects, engineers, and researchers. It offers a user-friendly approach to developing a project. PVsyst has a large database of meteorological data for several sites all over the world. It also provides manual insertion of measured data for sites that are not enlisted in the software. It presents results in the form of a full report which includes specific graphs and tables [26]. The data can be exported for use in other software. To obtain results, we have to provide some inputs to the software. Simulation variables in PVsyst are meteorological data, incident irradiance in collector plane, incident energy factors, PV array (field) behavior, inverter losses, system operating conditions and normalized performance index.

CHAPTER 4: DATA COLLECTION

During this research, both primary and secondary data were collected from various sources, such as Rwanda Energy Group (REG), which provide information from Mukungwa HPP, Rwanda meteorological agency (RMA) provided solar radiation data from Ruhengeri station. The data also was downloaded from homer storage.

4.1 Primary data collection

The primary data collected include monthly power produced from the selected plant. All of those data have been collected through contacts of the concerned institution. See Appendix A.

4.2 Secondary data collection

This method was used to get solar radiation of the selected area that has been provided by HOMER software by selecting Musanze location and then downloading the data from that location including data of irradiation and clearness index. Extra information relevant to the study was gathered by reviewing reports, academic journals, and other scientific publications.

4.3 Solar radiation potential of the selected area

For the case study, solar irradiation data were given by HOMER. Solar radiation is the energy radiated from the sun in the form of electromagnetic waves, including visible and ultraviolet light and infrared radiation. Photovoltaic technology is used to generate electricity from that energy radiated from the sun. The given global solar radiation data is expressed in KWh/m^2/day.

4.4 Monthly global radiation profile for the selected village

In this section, we discuss about the monthly global radiations for the selected villages in Musanze district. According to the Table 4.1, it is shown that Average Solar Global Irradiance for the Month of February is the highest value of the year.

Table 4. 1 Monthly global radiation profile for the selected village.

Month	**Clearness index**	**Monthly Average Solar Global Irradiance (GHI) (kWh/m² /day)**
January	0.480	4.900
February	0.439	5.170
March	0.478	5.030
April	0.487	4.930
May	0.504	4.800
June	0.526	4.810
July	0.528	4.900
August	0.501	4.920
September	0.485	5.000
October	0.450	4.690
November	0.453	4.640
December	0.465	4.690

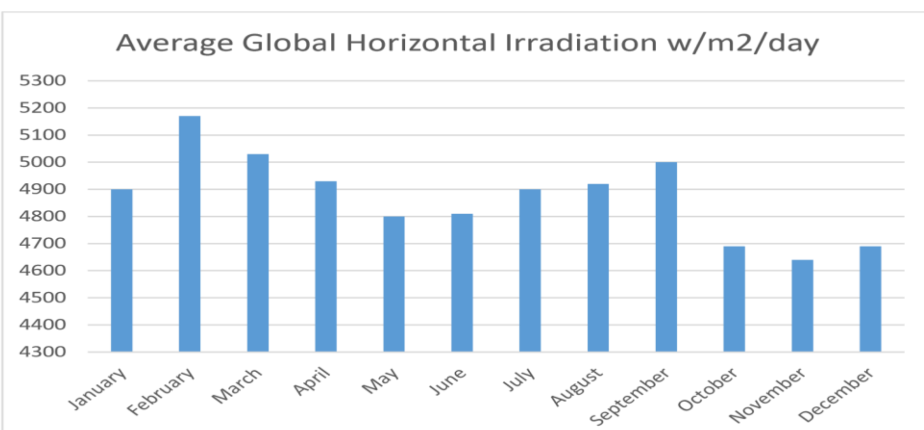

Figure 4. 1 Average Global horizontal irradiance for MUSANZE district.

4.5 Description of Mukungwa HPP

Mukungwa hydropower is located in Northern Province in Mukungwa cell, GACACAsector, MUSANZE district at 4km MUSANZE-KIGALI road. The dam is located at Ruhondo Lake, in which water is taken through a pressure channel of 2.5 m of internal diameter with a length of 2780 m. It is ended by a shaft (surge) tank of 8 m of internal diameter and 36 m of height. The penstock of 2.1m of internal diameter with a length of 285 m and is ended by being split into two sections toward two Francis turbines with a pressure of 14 bars with a vertical axis.

The installed capacity is 6MW per machine has an annual production of 48GWHs corresponding to 192 million cubic meters with a reserve of 22 GWHs, corresponding to 92 million cubic meters of water. This plant has been operating since 1981. It has two generators producing 6.6 kV on bus-bar, the voltage is supplied to a transformer 6.6/0.4kv with is a stepdown transformer to supply auxiliary equipment. On the same bus bar, there are two step-up transformers of 6.6/110kv, which supply a bus bar of 110kv with the interconnection of another power plant called NTARUKA, then the total power is transmitted to Kigali national control center called GIKONDO. Below is the table showing the power production from Mukungwa HHP on monthly basis for year 2020.

Table 4. 2 Monthly average power production (2020).

Monthly /Gen	GI in MW	G2 in MW	G1+G2 in MW	Deficit in MW
January	5.8	5.734	11.534	0.466
Fabruary	5.38	5.41	10.79	1.21
March	5.7	5.85	11.55	0.45
April	5.51	5.8	11.31	0.69
May	5.838	5.36	11.198	0.802
June	5.6	4.5	10.1	1.9
JULy	4.87	4.72	9.59	2.41
August	4.85	4.75	9.6	2.4
September	5.61	5.62	11.23	0.77
October	5.73	5.738	11.468	0.532
November	5.93	5.871	11.801	0.199
December	5.55	5.8	11.35	0.65

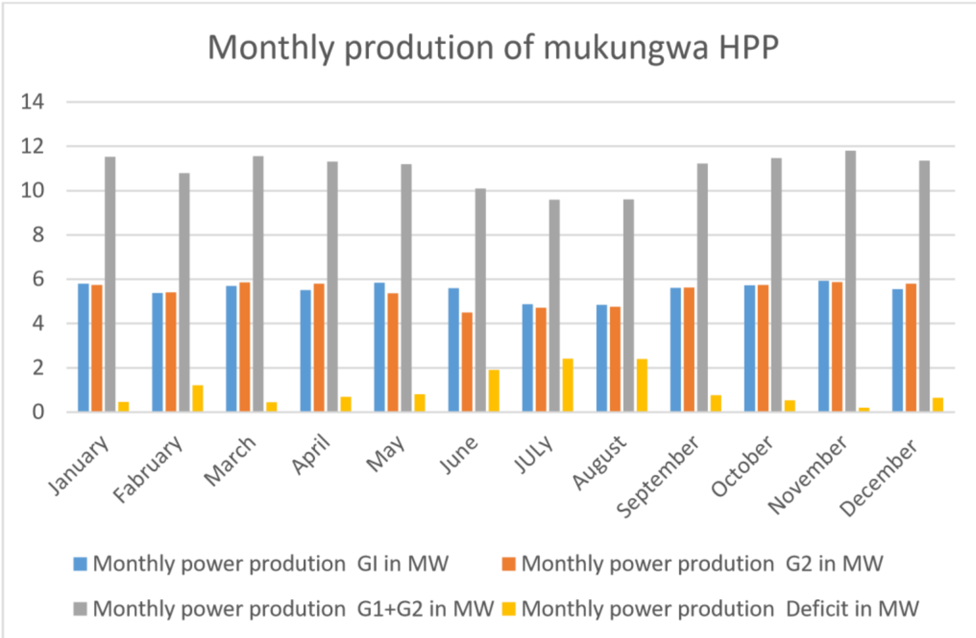

Figure 4. 2 Graph for monthly power production (2020).

Figure 4.3 and Table 4.2 show that there was the highest power deficit of around 2.41MW for July and August. Hence, we decided to design a solar photovoltaic of 3 MW to address this problem.

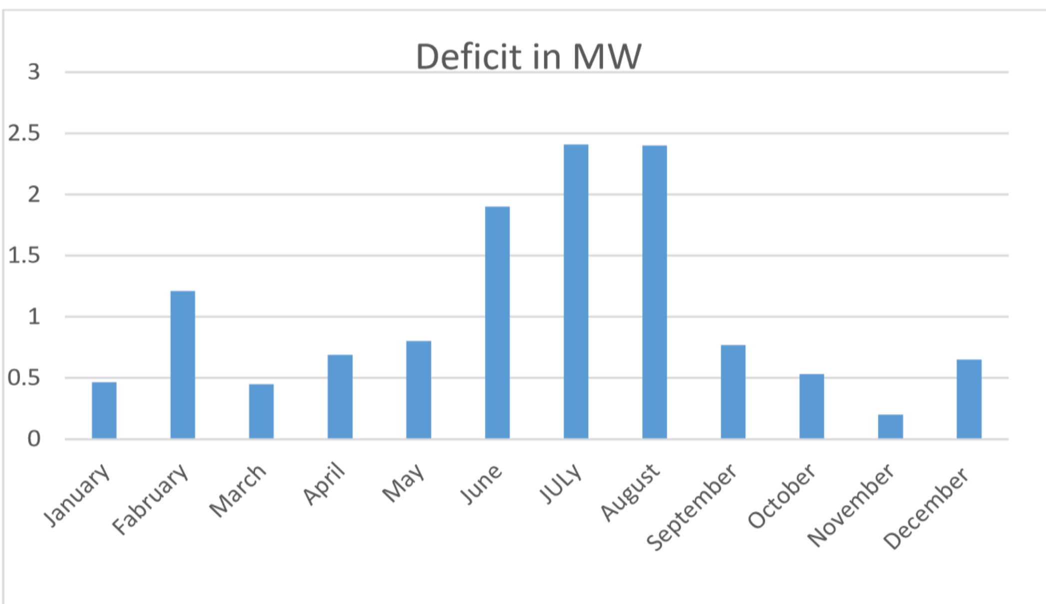

Figure 4. 3 Monthly power deficit.

CHAPTER 5: DESIGN AND SIMULATION

5.1 Design

5.1.1 Size the PV modules

Different sizes of PV modules will produce different amounts of power. To find out the sizing of PV module, the total peak watt produced needs. The peak watt (Wp) produced depends on the size of the PV module and the climate of the site location. We have to consider the “panel generation factor” which is different in each site location. To determine the sizing of PV modules, we evaluate the following parameters:

Evaluation of the total Watt-peak rating needed for PV modules

Before knowing the total wattage required, we conduct a load assessment where we sum up the total power for our case we have remark a deficit of 2410 kW.

Evaluation of the number of PV panels for the system

The number of PV panels for the system is obtained by dividing the total power required by the rated output Watt peak of the PV modules available to you. Increase any fractional part of the result to the next highest full number and that will be the number of PV modules required. If more PV modules are installed, the system will perform better. If fewer PV modules are used, the system may not work at all during cloudy periods. The more the number of solar panels results in high performance.

From the data collected, we have a maximum power deficit of around 2.41MW but due to the intermittence of the sun, we have decided to design a 3 MW PV System. This is done by selecting one module to have the power of 325W by referring to solar panels available on the market

Then, the maximum number of PV panels (modules) forming PV array of $\frac{3000kw}{0.325kw} = 9230\ to\ 9231$

The number of modules per string (NS) in series connection is given by Equation (5.1).

$$NS = \frac{System\ Voltage}{Module\ voltage} \tag{5.1}$$

$$NS = \frac{665}{30} = 22$$

Hence, almost 22 to 23 modules connected in series are required to satisfy the assumption; hence solving the described problem.

The number of modules in parallel (NP) is estimated by Equation (5.2).

$$NP = \frac{Number\ of\ module\ required}{Number\ of\ module\ per\ strimg} \tag{5.2}$$

$$NP = \frac{9230}{22} = 420$$

5.1.2 Orientation of solar panel for maximum power

For this design, the orientation of a solar panel for maximum power was estimated using the Tilt angle is 10^0 and the Azimuth angle of 0^0. This is also highlighted in Figure 5.1. The latter angles are selected in the way that losses are minimized to zero depending on the optimum irradiations.

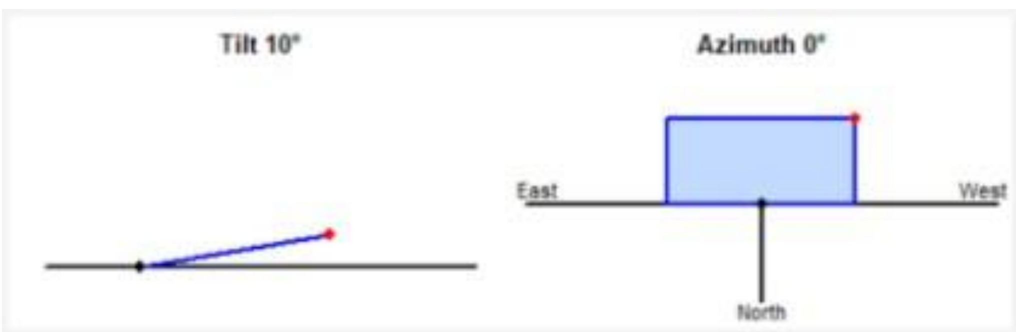

Figure 5. 1 Tilt Angle and Azimuth Angle.

5.1.3 Inverter sizing

An inverter is used in the system where AC power output is needed. The input rating of the inverter should never be lower than the total watt of appliances. The inverter must have the same nominal voltage as the output of the PV array. For grid-tie systems or grid-connected systems, the input rating of the inverter should be the same as the PV array rating to allow for safe and efficient operation. An inverter of 3000 kW is selected. Using each inverter of 1000 kW, we can calculate the number of inverters (NI) required using Equation (5.3).

$$NI = \frac{Total\ power\ required}{Rating\ of\ one\ inverter} \tag{5.3}$$

$$NI = \frac{3000kw}{1000kw} = 3$$

Since the used software doesn't have a nominal power of 1000 kW, an inverter of 990 kW was selected because its nominal power is closer to 1000 kW. However, the number of inverters remains unchanged.

5.1.4 Bloc diagram for PV system

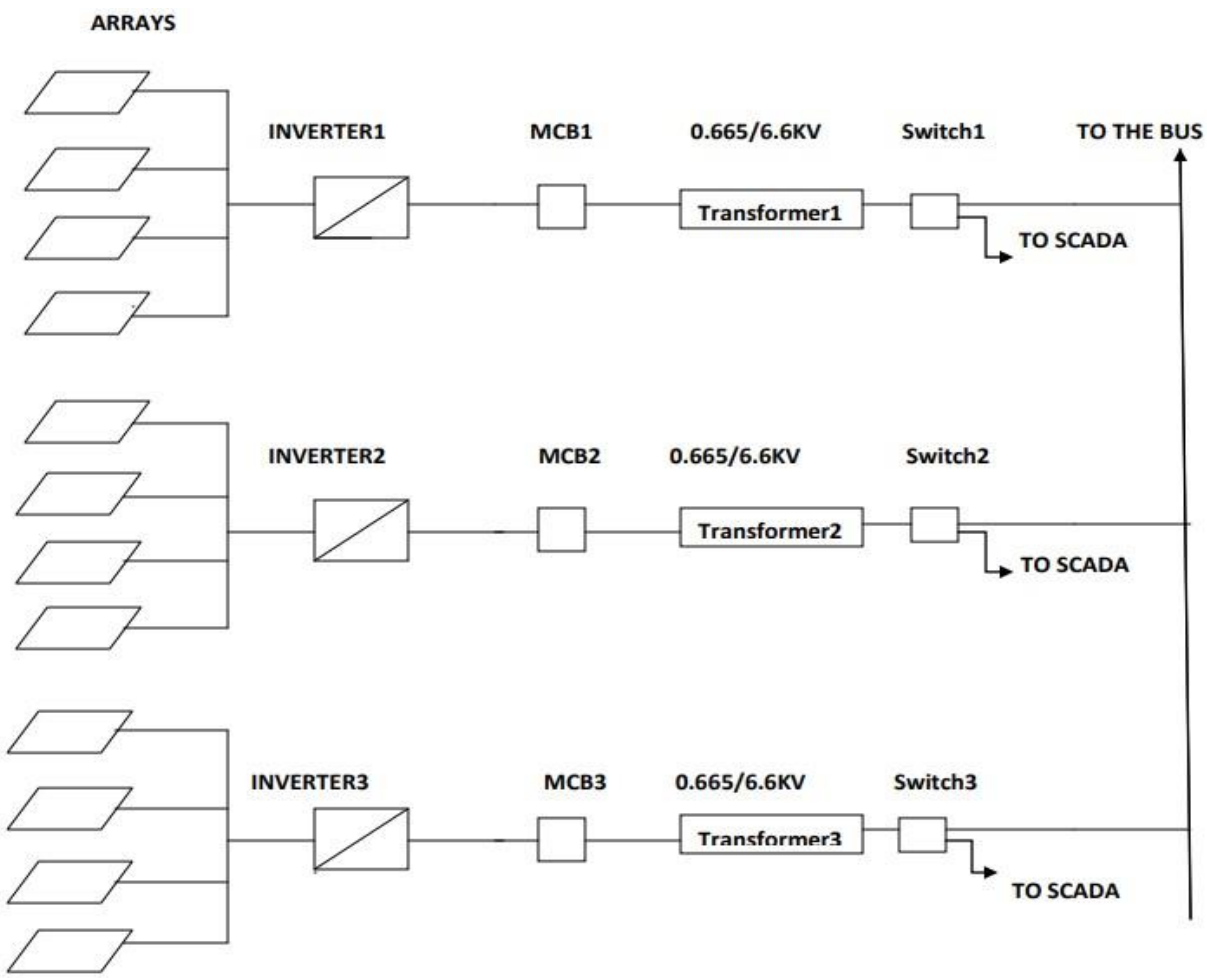

Figure 5. 2 Block diagram for PV Plant.

According to the block diagram above we have three part and each can produce 990kw according to the design, the PV array are connected to inverter (PCUs) for changing DC into AC, we have also step up transformers for increasing level of voltage, a SCADA system is used to control all parameter before injecting power into the grid. Circuit breakers are there for the purpose of switching and protection.

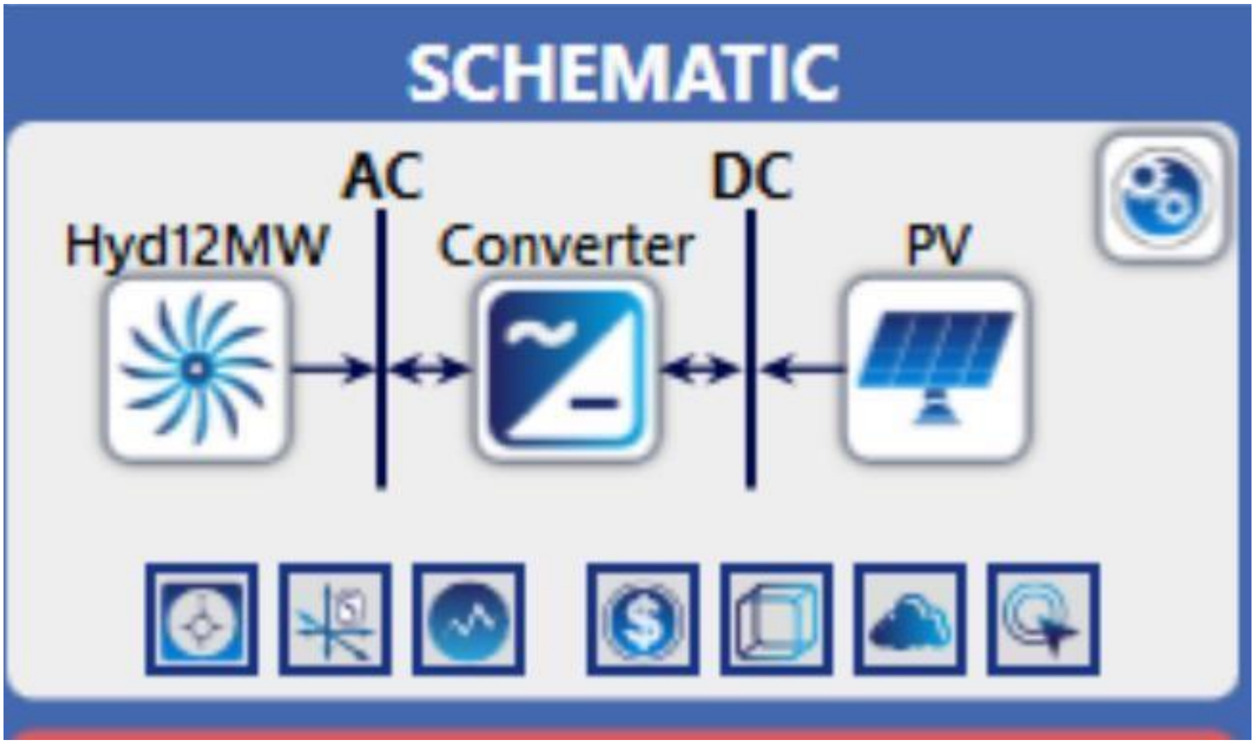

Figure 5. 3 Block diagram for hybrid in HOMER software.

5.2 Simulation

5.2.1 Characteristics of PV module

PV Array Characteristics					
PV module	Si-mono	Model	**LG 325 N1C-A5**		
Original PVsyst database		Manufacturer	LG Electronics		
Number of PV modules		In series	22 modules	In parallel	420 strings
Total number of PV modules		nb. modules	9240	Unit Nom. Power	325 Wp
Array global power		Nominal (STC)	**3003 kWp**	At operating cond.	2728 kWp (50°C)
Array operating characteristics (50°C)		U mpp	665 V	I mpp	4100 A
Total area		Module area	**15828 m²**	Cell area	14320 m²

5.2.2 Characteristics of Inverter

Inverter	Model	**Sunny Central-990CP-KR**		
Original PVsyst database	Manufacturer	SMA		
Characteristics	Unit Nom. Power	**990 kWac**	Oper. Voltage	596-850 V
Inverter pack	Total power	**2970 kWac**	Pnom ratio	1.01
	Nb. of inverters	3 units		
Total	Total power	**2970 kWac**	Pnom ratio	1.01

PV Array loss factors

PV Array loss factors				
Thermal Loss factor	Uc (const)	20.0 W/m²K	Uv (wind)	0.0 W/m²K / m/s
Wiring Ohmic Loss	Global array res.	2.7 mΩ	Loss Fraction	1.5 % at STC
Module Quality Loss			Loss Fraction	-0.8 %
Module mismatch losses			Loss Fraction	2.0 % at MPP
Strings Mismatch loss			Loss Fraction	0.10 %

Incidence effect (IAM): Fresnel AR coating, n(glass)=1.526, n(AR)=1.290

5.2.3 Simulation results

Grid-Connected System: Main results

Project : **STD**

Simulation variant : **New simulation variant**

Main system parameters	System type	**No 3D scene defined, no shadings**		
PV Field Orientation	tilt	10°	azimuth	0°
PV modules	Model	LG 325 N1C-A5	Pnom	325 Wp
PV Array	Nb. of modules	9240	Pnom total	**3003 kWp**
Inverter	Model	Sunny Central-990CP-KR	Pnom	990 kW ac
Inverter pack	Nb. of units	3.0	Pnom total	**2970 kW ac**
User's needs	Unlimited load (grid)			

Main simulation results				
System Production	**Produced Energy**	**4556 MWh/year**	Specific prod.	1517 kWh/kWp/year
	Performance Ratio PR	85.39 %		

5.2.4 Performance analysis

Figure 5.4 shows how much energy that we can produce per year with our PV Plant of 3MW due to the loss issue the power output was 2970 kW, and the loss is shown on the graph in green color. There are also other losses called collection losses caused by PV array connections. Those losses are shown in blue color in Figure 5.4. According to the graph, the energy produced in June, July and August is high while in the case of power deficit is high. Therefore, compensation is possible.

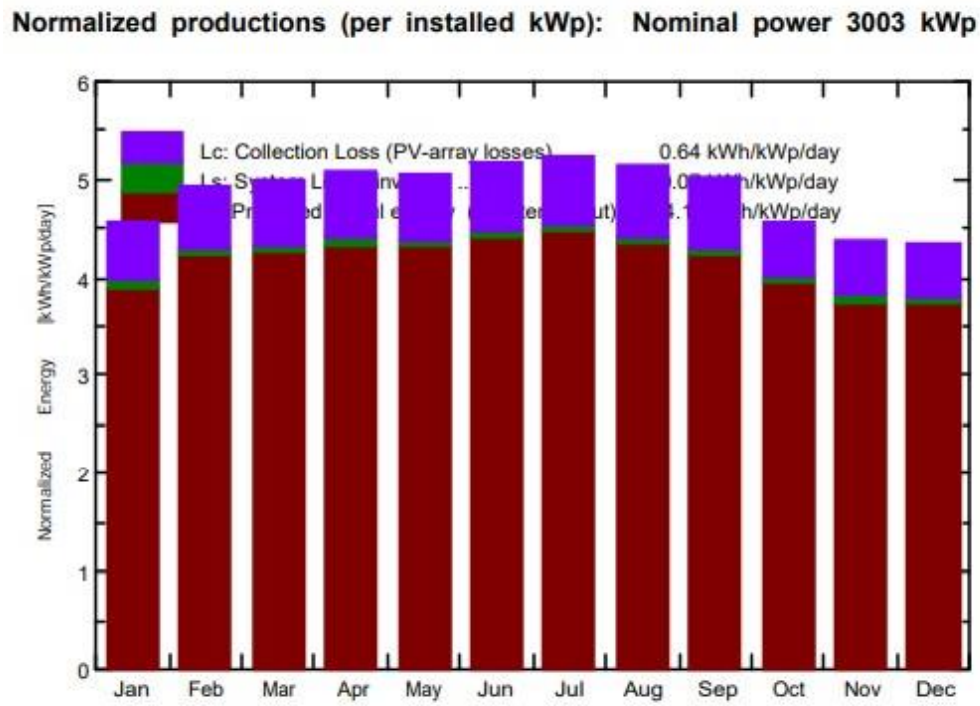

Figure 5. 4 Graph for normalized production.

5.2.5 Performance ratio

Performance ratio (PR) is the ratio of measured output to expected output for a given reporting period based on the system name-plate rating. A performance index is a ratio of measured output to expected output for a given reporting period based on a more detailed model of system performance than the performance ratio. According to the National Renewable Energy Laboratory (NREL), the standard performance ratio for a new PV system is a mere **77%**; and over time, the performance of the system is assumed to degrade. The performance ratio of our PV plant is high compared to the one given by the National Renewable Energy laboratory. That is about **85.4%.**

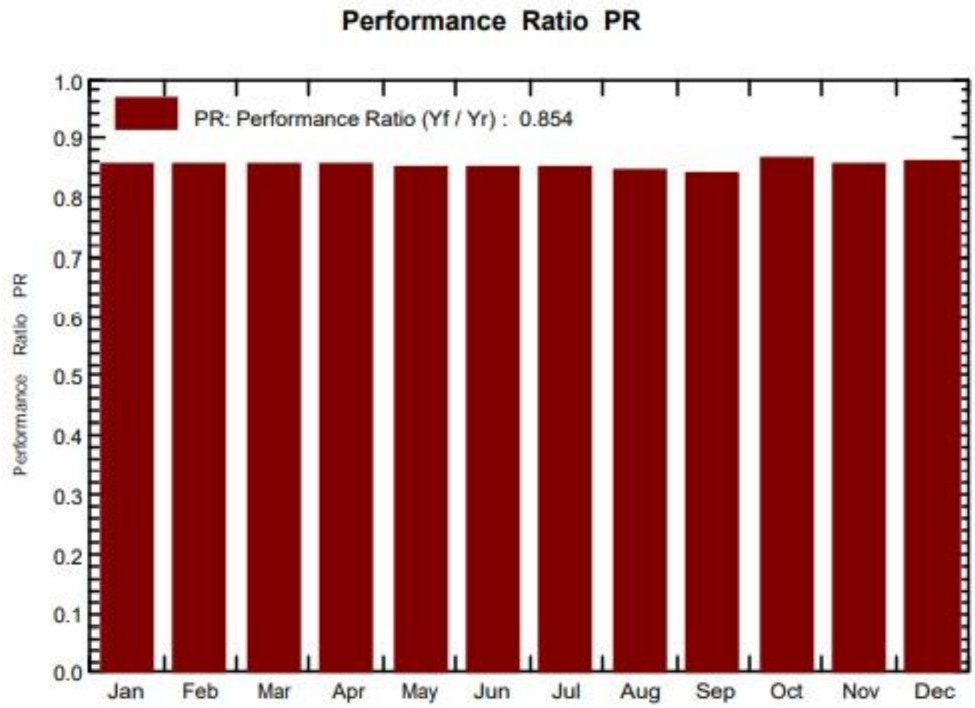

Figure 5. 5 Performance ratio.

The following shows the yearly average values for the simulated parameters in PVSyst Sofware.

Table 5. 1 Balance and Main results.

Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray MWh	E_Grid MWh	PR ratio
January	151.9	66.96	19.73	141.4	137.1	369.7	363.4	0.856
February	144.8	63.00	20.58	138.2	134.5	361.2	355.3	0.856
March	155.9	72.54	20.14	154.8	151.0	403.4	396.8	0.854
April	147.9	65.10	19.71	151.9	148.7	396.5	390.0	0.855
May	148.8	60.76	20.79	156.9	153.7	407.7	401.0	0.851
June	144.3	54.60	21.30	154.7	151.6	402.8	396.1	0.853
July	151.9	57.35	21.48	162.4	158.9	421.6	414.8	0.851
August	152.5	63.55	22.03	159.0	155.6	411.5	404.8	0.848
September	150.0	67.20	21.35	150.3	146.7	386.7	380.3	0.843
October	145.4	70.68	19.63	141.4	137.8	373.9	367.7	0.866
November	139.2	65.70	19.05	131.3	127.3	344.1	338.4	0.858
December	145.4	66.03	19.11	134.3	130.0	353.1	347.2	0.860
Year	1778.0	773.47	20.41	1776.6	1732.8	4632.2	4555.7	0.854

Legends:

GlobHor	Global horizontal irradiation	GlobEff	Effective Global, corr. for IAM and shadings
DiffHor	Horizontal diffuse irradiation	EArray	Effective energy at the output of the array
T_Amb	T amb.	E_Grid	Energy injected into grid
GlobInc	Global incident in coll. plane	PR	Performance Ratio

Grid-Connected System: Special graphs

Project : **STD**

Simulation variant : **New simulation variant**

Main system parameters	System type	**No 3D scene defined, no shadings**		
PV Field Orientation	tilt	10°	azimuth	0°
PV modules	Model	LG 325 N1C-A5	Pnom	325 Wp
PV Array	Nb. of modules	9240	Pnom total	**3003 kWp**
Inverter	Model	Sunny Central-990CP-KR	Pnom	990 kW ac
Inverter pack	Nb. of units	3.0	Pnom total	**2970 kW ac**
User's needs	Unlimited load (grid)			

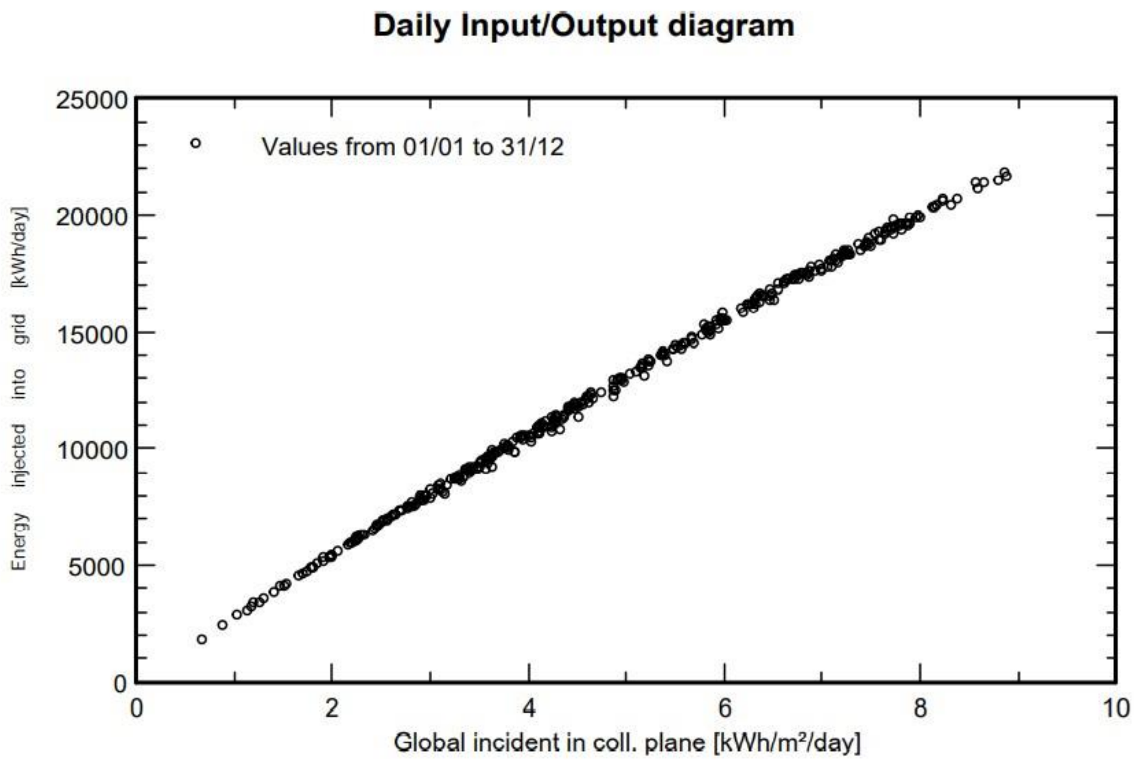

Figure 5. 6 Global incident in coll plane.

5.2.6 Daily input/output diagram

The diagram above shows how much the energy (kWh/day) injected in the grid increase global incident in coll plane increases (kWh/m^2/day).

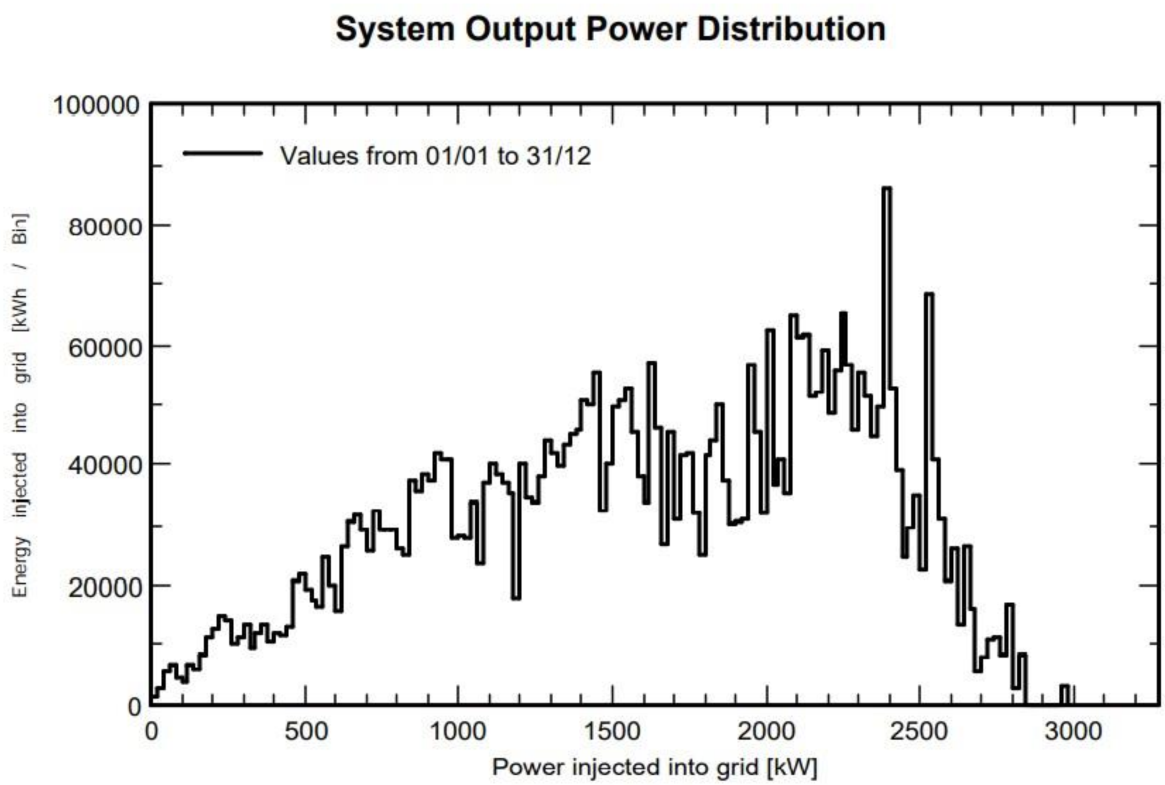

Figure 5. 7 System output Power Generation.

The graph above shows how much power is injected into the grid and how much energy will be produced at that time. According to the graph, it is not linear due to the intermittence of the sun.

Grid-Connected System: Loss diagram

Project : **STD**

Simulation variant : **New simulation variant**

Main system parameters	System type	**No 3D scene defined, no shadings**		
PV Field Orientation	tilt	10°	azimuth	0°
PV modules	Model	LG 325 N1C-A5	Pnom	325 Wp
PV Array	Nb. of modules	9240	Pnom total	**3003 kWp**
Inverter	Model	Sunny Central-990CP-KR	Pnom	990 kW ac
Inverter pack	Nb. of units	3.0	Pnom total	**2970 kW ac**
User's needs	Unlimited load (grid)			

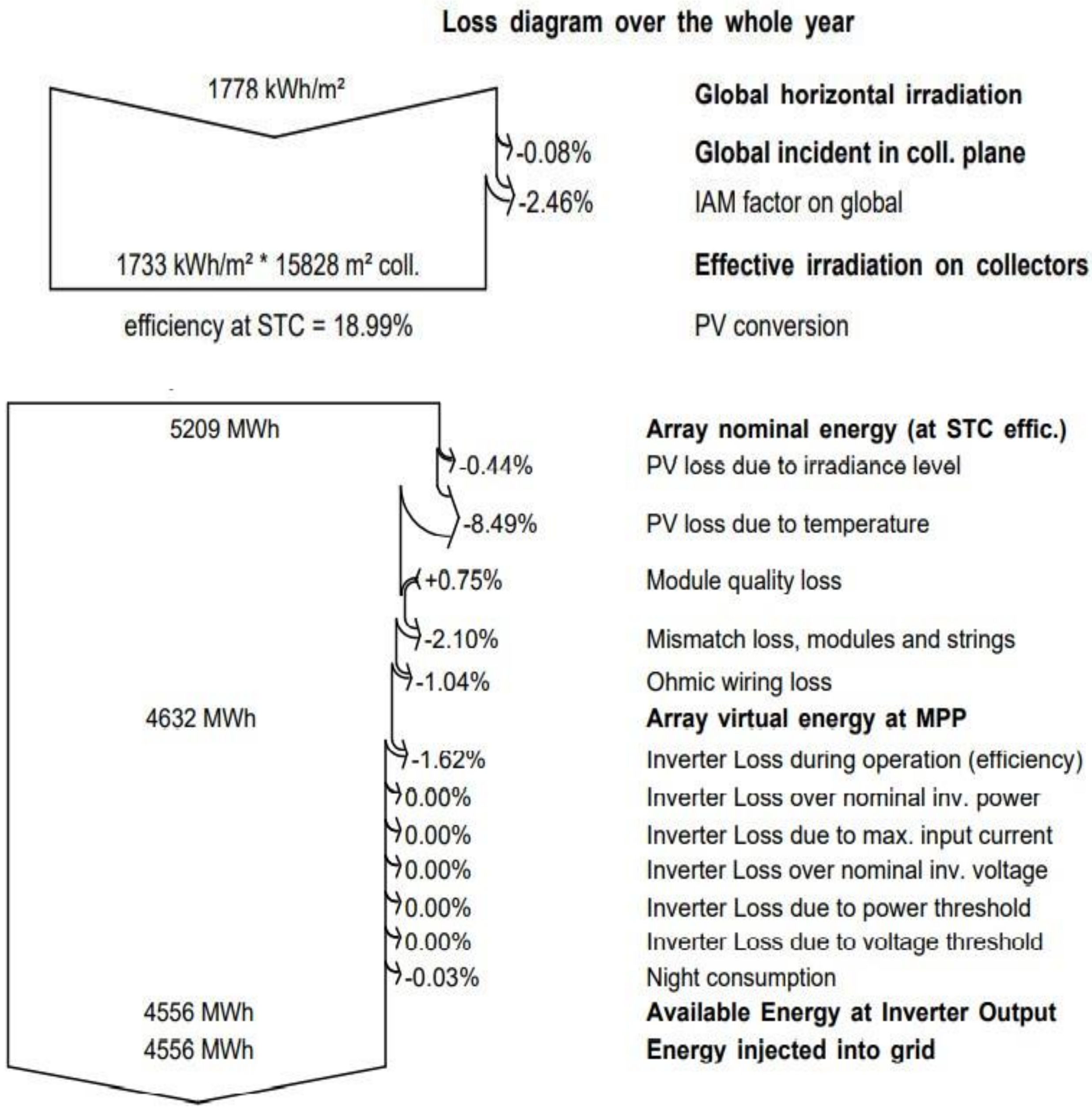

Figure 5. 8 Loss diagram over the whole year.

The diagram above is showing the detail of losses for the system over the whole year.

5.3 Cost details

This section highlights different parameters used to evaluate the project. The Table 5.2 indicates the required parameters considered for this evaluation. This table also shows different cost for every item.

Table 5. 2 Cost details.

Nº	Item	Cost In US Dollars
1	PV Arrays totaling to 3 MWp	5,900,000
2	Inverter (PCUs)	730,000
3	Mounting structures	407,000
4	Cables & Hardware	67,000
5	Junction box & distribution boxes	12,000
6	Lightning Arrester, Earthing kit	16,300
7	PVC pipes & accessories	4,000
8	Spares	6,700
9	SCADA system	27,000
10	Design, engineering, quality surveillance, testing, transportation, insurance coverage,	245,000
11	Erection & Commissioning	404,000
12	Taxes and VAT	143936.64
	Total Supply of Equipment (for 3 MW)	**7,962,937**

5.3.1 Cost of energy and calculations of payback period

The energy produced per annum is 4556 MWh/Year According to the data from the software. The cost per Kwh is 0.25USD according to REG

5.3.2 Levelized cost of energy (LCOE) calculation

The LCOE measures lifetime costs divided by energy production. It calculates the present value of the total cost of building and operating a power plant over an assumed lifetime. It also allows the comparison of different technologies (e.g., wind, solar, natural gas) of unequal life spans, project size, different capital costs, risk, return, and capacities. This is estimated by Equation (5.4).

$$Annual\ cost\ = Initial\ costs\ + annual\ expenses\ = \mathbf{7,962,937}\ \boldsymbol{USD}$$

$$\mathbf{LCOE} = \frac{\boldsymbol{It+Mt+Ft}}{\boldsymbol{Et}} \tag{5.4}$$

Where $\boldsymbol{It}$ is an investment expenditure in year t (including financing), $\boldsymbol{Mt}$ is an operation and maintenance expenditures in year $\boldsymbol{t}$, Ft is the fuel expenditures in year t.

Hence, $LCOE = 7{,}962{,}937/4556000 = \mathbf{0.174}\ \boldsymbol{USD/Kwh}$ **.** This cost is less than the cost of electricity at the Rwandan power utility.

5.3.3 Net Present Value (NPV)

The Net present value method is one of the modern methods for evaluating project proposals. In this method, cash inflows are considered with the time value of the money. The Net present value describes as the summation of the present value of cash inflow and the present value of cash outflow. The Net present value is the difference between the total present value of future cash inflows and the total present value of future cash outflows.

5.3.4 Decision about the project

Project is accepted if NPV > 0. The software generates the following results:

Year 1 Electricity Savings (kWh):	**4556000**
Annual Output Degradation (linear):	**0.60%**
Cost per kWh:	**0.17USD**
Investment:	**7,962,937 USD**
Future Value Discount Rate:	**6.00%**
Gross Present Value:	**9,040,423.86 USD**
Net Present Value:	**1,077,486.86 USD**

Compared to the viability conditions, the project produces a Net Present Value of 1,077,486.86 USD which is a positive NPV. Hence, the project is feasible.

CHAPTER 6: CONCLUSION AND RECOMMENDATION

6.1 Conclusion

In this research, it was found that Mukungwa HPP power deficit can be complemented by the installation of the 3MW PV plant. By analyzing the location, it is seen that the yearly average irradiation is 4.87 kWh/m^2/day which is enough to produce the required power for compensating deficit. Therefore, the simulation shows that the power of 2970 kW can be produced which is above the highest power deficit of the plant. This deficit is equal to 2.41 MW that occur in July. In that month, we have high evaporation of water in the dam due to the high sunshine period. The Power from PV is also slightly higher due to sun intermittence. However, if there is a power deficit at Mukungwa HPP, diesel generators are used, but they produce high CO_2 emissions which is the source of global warming; and cause the increase of cost per kWh due to high running costs.

Therefore, my research simulation shows that diesel can be replaced by the installation of a PV system that is clean, reliable and affordable energy. This research show also the performance of 5% in terms of reliability. The low cost per KWh is also expected from the installation of the said system. Also, the proposed PV system is installed closer to the HPP to avoid the cost of the transmission line. It is shown that when the power from the PV is high, the production from HPP is reduced so that the water in the dam is sufficient to be used during peak demand. And that water can be used when PV has no longer producing especially during the night. Economic analysis also shows a net present value equal to 1,077,486.86USD which is positive, indicating the viability of the project.

6.2 Recommendations

From the work done, we can recommend the concerned institution to apply this project because it can reduce the effect of the CO_2 emission as well as reduction of power import. According to the seventh sustainable developments goal, investing in solar, wind and thermal power, improving energy productivity, and ensuring energy for all is vital. If we are to achieve SDG 7 by 2030, We recommend further work to deeply analyze the whole country. We may have enough amount of power in terms of Gigawatt from the sun.

We also recommend the government of Rwanda especially the ministry of education to put the effort into the solar technology area. Because it can be used in cooking, heating water as well as the production of electricity.

We further recommend the University of Rwanda (UR) cooperate with companies at a high level so that the research can be based on the existing issue in the industrial area. UR is also recommended to provide research fees for students to facilitate data collections on the field, especially for postgraduate studies.

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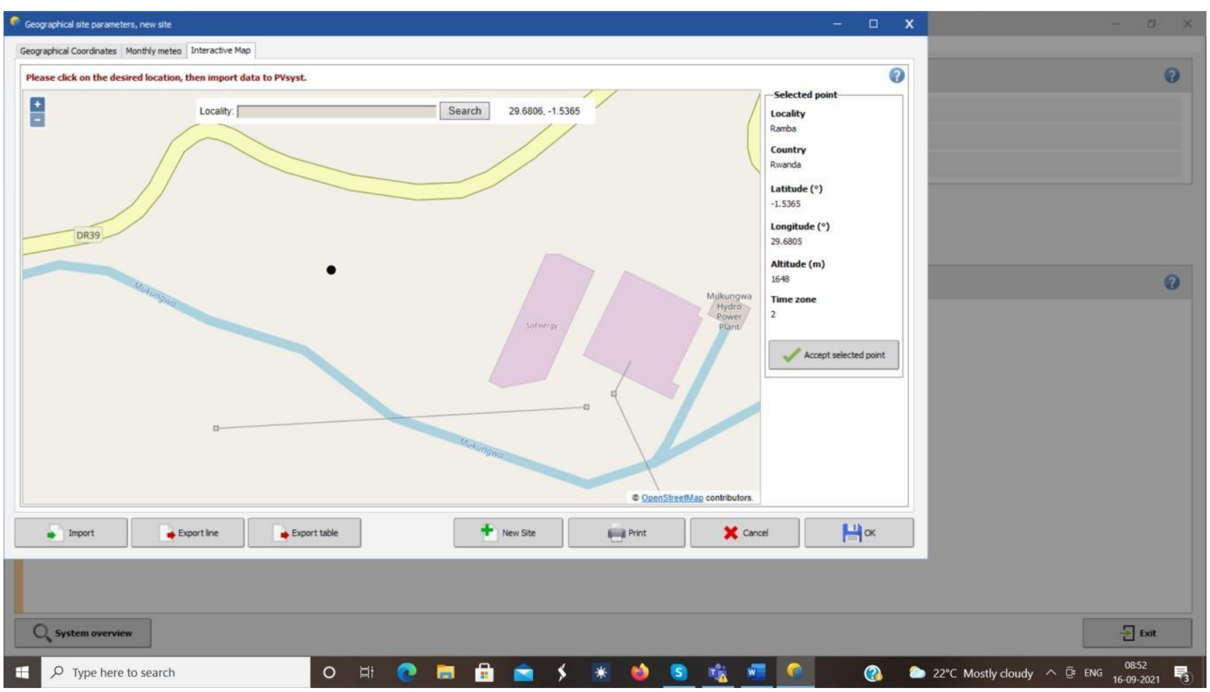
APPENDICES

Appendix A

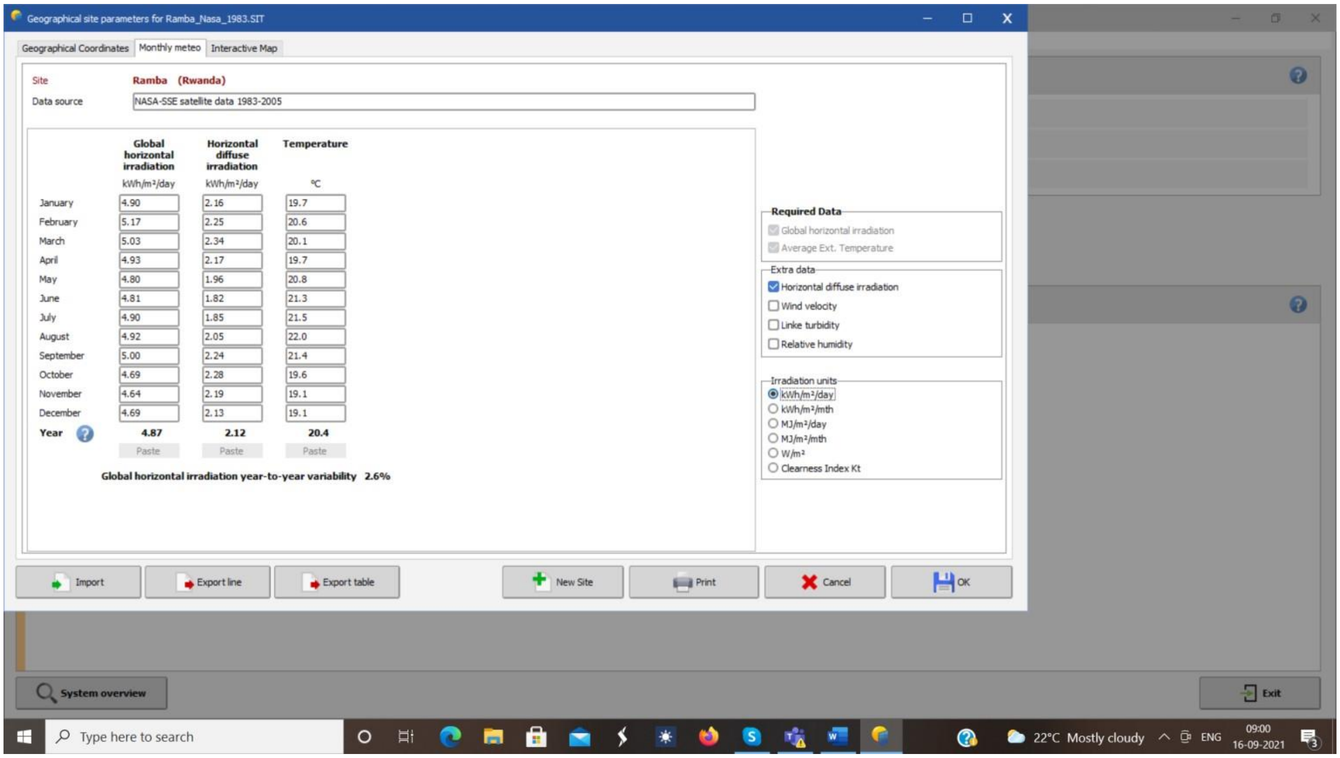
Monthly /Gen	G1 in MW	G2 in MW	G1+G2 in MW
January	***5.8***	***5.734***	**11.534**
Fabruary	***5.38***	***5.41***	**10.79**
March	***5.7***	***5.85***	**11.55**
April	***5.51***	***5.8***	**11.31**
May	***5.838***	***5.36***	**11.198**
June	***5.6***	***4.5***	**10.1**
JULy	***4.87***	***4.72***	**9.59**
August	***4.85***	***4.75***	**9.6**
September	***5.61***	***5.62***	**11.23**
October	***5.73***	***5.738***	**11.468**
November	***5.93***	***5.871***	**11.801**
December	***5.55***	***5.8***	**11.35**

Appendix B

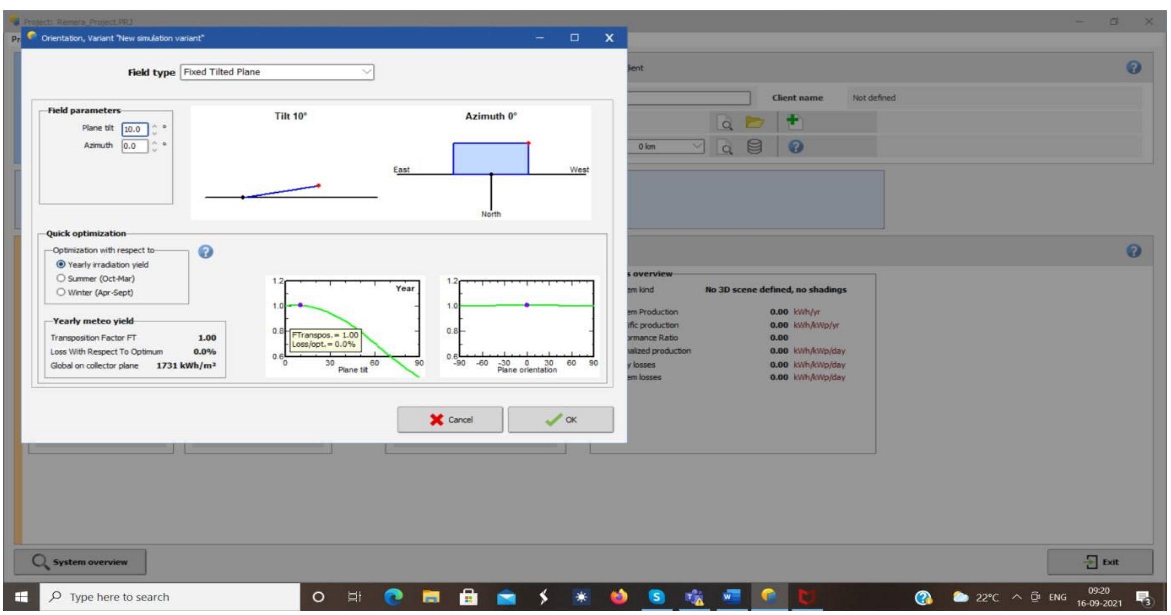
Pointing on real location using PVsyst software.



The dot shows where the pv should be installed.



Global irradiation from the selected site in kwh/m^2/day.



At tilt angle of 10 degrees, where loss with respect to optimum is zero.