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TECHNO-ECONOMICS ANALYSIS OF 4.5MWp SOLAR PV POWER PLANT AT KINAZI SECTOR-RWANDA

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Abstract

Rwanda has had remarkable economic growth in recent years, but energy generation is still a big bugbear in its development. Rwanda has a lot of energy resources but, only around 10 percent of the available resources are utilized for electricity generation. This project work focuses on the exploitation of the sun which is an abundant and non-exhaustible resource of energy. The cost of the solar energy systems is analyzed and compared with other energy systems to emphasize the importance of interconnecting solar energy-based generation into the grid system for this particular area.

The PVsyst7.2.5 software for renewable energy modeling played a significant role while performing the techno economics analysis of the 4.5MWp PV power plant at Kinazi sector in Ruhango district; it provides the key performance indicators like the capacity factor, yield factor, Levelized cost of electricity, net present value, performance ratio, payback period and the internal rate of return. After analyzing the results related to the solar PV performance indicators related to the site where Ruhango Provincial hospital is located, the study has proven that the investment in solar PV power plants for electricity generation in the specified area is feasible and profitable. From the simulation done, internalizing all necessary financial and technical parameters for Ruhango provincial hospital solar PV power plant, it has been found that the project is profitable and within 12 years, the total cost invested would have been recouped.

Ruhango provincial hospital houses can support fifteen thousand solar PV panels that can yield 6993108kWh per year. This generation will make a considerable impact on the national installed capacity supplying the hospital, and the neighboring citizens, and the excess energy will be injected into the national grid.

1. Introduction

From the geographical location of Rwanda, it was found that there is a high potential to generate electricity from solar radiation with 4.5 kWh per m^2 and approximately 5 peak sun hours.[1] Despite the solar radiation potential, Rwanda has only five solar power plants that generate total solar energy of 12.23MW one of which produces 8.5MW. The government of Rwanda aims at increasing the number of solar power plants to reduce the cost of production and utilize the available renewable energy sources in Rwanda. [1] Rwanda is globally well-positioned because it has enough access to solar radiation that is suitable for electricity generation. The solar energy generation in Kinazi sector of Ruhango district will be utilized as the main supply (off-grid) or as the backup source of electricity which can take over the supply of the latter area in case of interruption from the mains and will also support the national grid in case of imbalance between the generation and the demand. The dependence on solar energy is still very little in Rwanda and the hydropower generation is not enough to satisfy the country's population. The following table shows the plants available in the country. [3]

Table 1: Available solar energy power plants in Rwanda

Name of the plant	Generation capacity	Construction period	Type of connection	District location
Rwamagana solar power plant	8.5 MW	2014	On-grid	Rwamagana
Nasho solar power plant	3.3 MW	2015	Off-grid	Kirehe
Mont jali solar power plant	0.25 MW	2007	On-grid	Gasabo
Ndera solar power plant	0.15 MW	2016	Off-grid	Gasabo
Nyamata solar power plant	0.03 MW	2016	Off-grid	Bugesera

Solar energy in Rwanda like in other countries is being utilized in solar thermal conversion and solar electric conversion. In solar thermal conversion, the fluids are heated until the steam is produced to use for driving large-scale turbines. In solar electric conversion, the sunlight is directly converted into electric power through a photocell. Microgrid projects are rising in East African countries as well as globally because the cost of renewable energy technologies is becoming low. Solar PV modules and battery storage mini-grids, microgrids, and Nano grids are known as electric generators or energy backup systems that may be interconnected to the national grid network, providing electrical energy to a number of the customer population. [4] The implementation of this solar PV power plant is in line with the national target which is to reduce 8.5% of the total greenhouse gases emission by 2030 and increase electricity access up to 100% [5]

2. Background of the Project

Rwanda is a landlocked country, a member of East African countries. Its area is 26,338km2; the free land extends on 24,948 km2 while the water covers 1,390km2. Referring to Rwanda's 4th Population and Housing Census done in 2012 (NISR), Ruhango district was populated by 319,885 citizens with 52.5% of females and it was ranked among three populated districts as it 510 inhabitants/km2. Kinazi sector is among nine sectors of Ruhango district and is populated with 43,658 citizens (20,926are male and 22,732 are females). [1]

As of May 2021, in the Ruhango district, 53% of the population are on-grid connected while 24.2% are off-grid connected, which implies that the access rate in this district is 77.2%. [2][3] Apart from the dense population in the district, there are some government and private institutions that are providing valuable services to the nearest population, such as the Ruhango provincial hospital which is known as Ruhango provincial hospital, and the agricultural projects dealing with cassava plants which was found very relevant in this region and so on.

Rwanda is among the blessed countries with having different resources of electricity such as solar, biomass, methane gas, geothermal, hydro, and wind which is at its infancy stage in data gathering with a lot of natural resources. Both on-grid and off-grid connection approaches were adopted in Rwanda, so that the access to electricity may be accelerated to meet the national target. 63% of Rwandan households are currently having access to electricity. These include 47% connected to the national grid and 16% accessing through off-grid solutions. The plan is 100% access by 2024. [4]

From the report made by Rwanda Energy Group (REG), the total energy generated by the generating plants that are operating in Rwanda is 235.6 MW where the hydrological resources are dominating. Only 11% of the available capacity is imported while 89% is generated inside the country. 50.6% is generated from hydrological resources, thermal resources are 43.4% and solar resources are 5%. [1] The Rwanda Energy Group (REG) is making progress in its ambitious target to add more consumers to the national grid by connecting several homes, including healthcare centers in Ruhango District. This is in a bid to achieve the 100% access target by 2024; currently, in Ruhango District, we are at 42% with 31% of the households connected to the national grid, while 11% are accessing power through off-grid solutions, mainly solar energy. Though there is an increase in the number of connections, the proportionality of generation and demand is not linear, this results in power shortages that occur some hours a day. The lack of electricity has a considerable impact on the efficient provision of services to patients at the hospital and other services requiring electricity. Ideally, the installed capacity for Rwanda should be 13GW for the present population. The country can't make an increase in generation from 235.6 MW up to 13GW but the government aims at providing reliable electricity access to all citizens of the country by 2024.[2][3]

Electric power has been an important tool for the social and economic development of the population all over the world. Electricity is one of the greatest inventions that has been made by man and has improved health and standards of living for humankind at an unimaginable level; since people have developed various methods of utilization of electricity in different forms depending upon what they want to use it. The site was selected based on several indicators such as the population density of the selected sector, the sensitivity of energy on services offered to the citizens of the mentioned location, or the accessibility and economic projects conducted in the same area. The microgrid system was found as a golden that links social equity, economic growth, and environmental sustainability. Rwanda is among the countries that are putting much effort into economic development and poverty reduction through different strategies. One of them is to increase the rate of electrification, especially in rural areas. Frequent outages are caused by the imbalance between the supply and the demand which rises every day because the country's population also increases and another sector like the industrial activities and the living standards of the population improves every day.[3]

3. Objectives

3.1. General Objective

The main objective of this project is to perform the techno-economic analysis of a grid-connected 4.5MWp solar PV power plant which is going to be implemented in Ruhango district, Kinazi sector, in Rwanda.

3.2. Specific Objectives

The hybridization of non-exhaustive resources of energy will enhance the energy system reliability, proficiency, and economy in Ruhango district and will also enable us to:

- Assess the solar energy potential for the kinazi sector, Ruhango District, Rwanda.
- Evaluate the declination of the reliance on national grid power and increasing clean energy generation for the sampled region.
- Estimate the economic viability of exploiting the solar PV power plant to minimize the power shortage in the Kinazi sector, Ruhango district in Rwanda.
- Promote the exploitation of renewable energy resources preventing a run out of the conventional energy resources

4. Literature Review

This chapter covers the theoretical knowledge of different fields related to this research. The focus was put on the identification of the findings from different researchers and related gaps. The use of renewable mini-grids in different areas which can also be connected to the national grid is becoming very important in increasing the reliability of supply for consumers, reducing the electricity bills as well as decreasing the dependence on the grid. The Kinazi solar PV power plant that will be interconnected will supply the nation's population through the nearest substations and operate autonomously as a single unit providing the quality supply to the nearest citizens. This mini-grid PV power system when working with the national grid will improve its efficiency and cost-effectiveness. Like other mini-grids, this one is intended to help balance the national grid system, supporting frequency control, and stabilizing the voltage enhancing the quality of power delivered to the population. [8]

Techno-economic evaluation of a grid-tied PV system in Adam city, Oman with 1MW. using the array size of 250Wp with around 4000 modules. The optimum size of the inverter, the payback period, the average CoE and various monthly tilt angles for maximization of the energy and peak power produced are to be considered in PV power systems, a lot of parameters related to the study of solar PV systems were considered and the research is very useful to the community of Adam city as well as other areas of this planet. [9] The techno-economic analysis for a tied grid PV-battery energy storage system to obtain the minimum annual operating costs for the three different scenarios was effectively conducted, i.e. the three analyzed system cases are, systems that have no battery energy storage (BESS), systems whose battery energy storage (BESS). The systems without peak load shaving and with both battery storage systems and peak load shaving were analyzed. The grid-connected PV battery energy storage is very useful as it is one of the energy generates approaches that is CO_2 emission-free and quick in rural electrification strategy. [10]

The sun is a free, abundant, inexhaustible, and environmentally friendly energy resource that can be converted into various forms of energy for different purposes. It has been found that the annual output of the sun received by the earth is 42,000 times the total annual earth energy consumption. Burning coal, fossil fuels, and oil have been used worldwide as the basic need of all nations. But these energy resources are nonrenewable and dangerous to the environment, all energy on earth primarily comes from solar energy. The main resources of power generation today are fossil fuels and nuclear reactions. Hydro energy is also used. Hydro energy does not produce adequate and consistent power for the nation’s consumption. Moreover, the exploration techniques for these resources are expensive. From the advanced technological approaches that are being globally exploited, the sun’s energy that strikes the earth was found enough to supply all forms of energy needed exhaustively and effectively.[11]

The National Air and Space Agency (NASA) and the University of Rwanda have assessed the solar energy resources and solar radiation in Rwanda. They have realized that the Eastern province has the highest solar energy potential among others. In 2007, another research was conducted by MININFRA and the department of meteorology where the average global solar radiation on monthly basis was estimated with the help of a meteorological data set. The research has shown that the daily solar radiation in Rwandan territory lies between 4 kWh/m² and 5.4 kWh/m², available in the north of Ruhengeri city and south of Kigali city and eastern province respectively. Even though It was also realized that the radiation varies concerning Rwandan season, the estimated daily average irradiation level in cloudy is about 4.5kWh/m^2 with a total annual potential estimated at 66.8TWh.[12]

The design of solar PV power plants to be used in rural electrification or area which are far from the national grid commonly known as remote areas has become a sustainable response in many countries. As the initial cost for building transmission lines that link this area with the grid is considerably high, the standalone photovoltaic systems have become a good solution. The design procedure of such systems consists of the choice and dimensioning of solar panels, battery storage, DC-AC inverters, and mini transmission grid to convey electricity to different households. [13]

There are generally two possible design approaches of electrical for PV systems. Grid-connected systems interact with the utility power grid and do not require battery backup capabilities, and standalone systems require battery backup. Even though the first type is to shut down whenever the sun shining is not available, it normally provides a big amount of bill savings. Nowadays, it is not essential to size the grid-connected PV system in such a way that it matches the daily demands of the user. When the PV system is silently generating green power, the grid is always available. When the green power generated is greater than the consumer's need, the excess power is fed back into the grid. However, when the PV system does not produce enough power, the grid will supply the consumer with power, which eliminates the need for battery storage and provides less system maintenance and more saving to the consumers [14]

5. RESEARCH METHODOLOGY

The analysis of techno economics feasibility of the photovoltaic power plant in the Ruhango district was conducted with the help of several methods and suitable software provided by the National Renewable EnerLaboratoryory (NREL) where the estimation of the unit cost of solar power project deployment for this area is calculated by using the Levelized cost of electricity (LCOE) approach of rooftop solar PV. The sensitivity analysis is done based on the LCOE parameters like the discount rate and the operation and maintenance (O&M) cost to test the robustness of the LCOE tool. The profitability analysis is done by using the net present value (NPV), internal rate of return (IRR,) and payback period to judge the worth of the project for this particular area. The solar PV panel will be mounted on the roofs of Ruhango provincial hospital houses.

5.1. **Documentation or Literature Survey**

Reference is made to different scholarly articles and other sources that are relevant to this project to get an overview of sources explored while researching projects that are similar to techno economics analysis of 4.5MWp PV power plant and to demonstrate to those who will read this project report how this research fits within a larger field of study. The researchers have found that 73.06% of the total area of Rwandan territory coverage is suitable for solar energy production with high and moderate production potential (42.48% of high generating potential and 30.58% with moderate generating potential) and Ruhango district was found among nine districts of the southern province which are suitable for solar energy generation; this implies that more 18,459 Km^2 of the available land across the country is suitable for PV power generation.[5]

The findings have also shown that solar PV power generation would be effectively applicable for areas that are hit by solar radiation which is above 1300kWh/m^2/year which is equivalent to 3.6kWh/m^2/day whereby Rwanda's territory is hit by the solar radiation that ranges between 3.52kWh/m^2/day to 5.5kWh/m^2/day; therefore, it was also found that Ruhango district solar PV suitability is at 85.64% while the households that are currently connected to the national grid are 54.2%.[5]

5.2. Physical Status of the Available Houses

The total area of the hospital is 84,552.54 m^2 while the area occupied by buildings is 25,300 m^2. The houses are strong enough to support several solar PV panels that will be mounted on top of the roofs. The available houses supporting a considerable number of solar PV panels have to be strong enough to carry the additional weight increased by the weight of panels and their supports used for tilting and fixing them on top of the roofs. Ruhango provincial hospital is a newly constructed hospital where all houses are new and their roofs are strong enough to support several solar PV panels that can be laid on them. The hospital will keep on expanding the building activities on its available land depending on the needs.

Figure 1: Picture of the available houses for Ruhango provincial hospital

5.3 Important Data Related to the Selected Site

After gathering all the available data on the concerned site, a techno-economic analysis will be conducted to judge the feasibility of the project. This will help us to select the best approach to be adopted to design and implement this project effectively.

5.3.1 Geographical Coordinate of Ruhango provincial hospital

From the Meteo data, NASA-SSE satellite data 1983-2005-Synthetic, the Ruhango provincial hospital is located in the southern province of Rwanda, Ruhango district which is the former Ntongwe district, in the Kinazi sector. It is located at the latitude of -2.19506^0 S, the longitude of 29.9058^{0}E, altitude of 1503m.

5.3.2 Solar resource

The data relating to solar radiation on the site were retrieved from the NASA-SSE satellite data 1983-2005, global and diffuse horizontal radiation is important in the design and modeling of the system since the amount of solar radiation, that reaches the site plays a great impact on solar energy generated by the solar PV power systems. The figure below shows the average monthly solar irradiation for the concerned site; The irradiance was calculated to be approximately 165 kWh/m^2/month for this location. The worst month is November with average irradiance of about 140 kWh/m^2 /month.

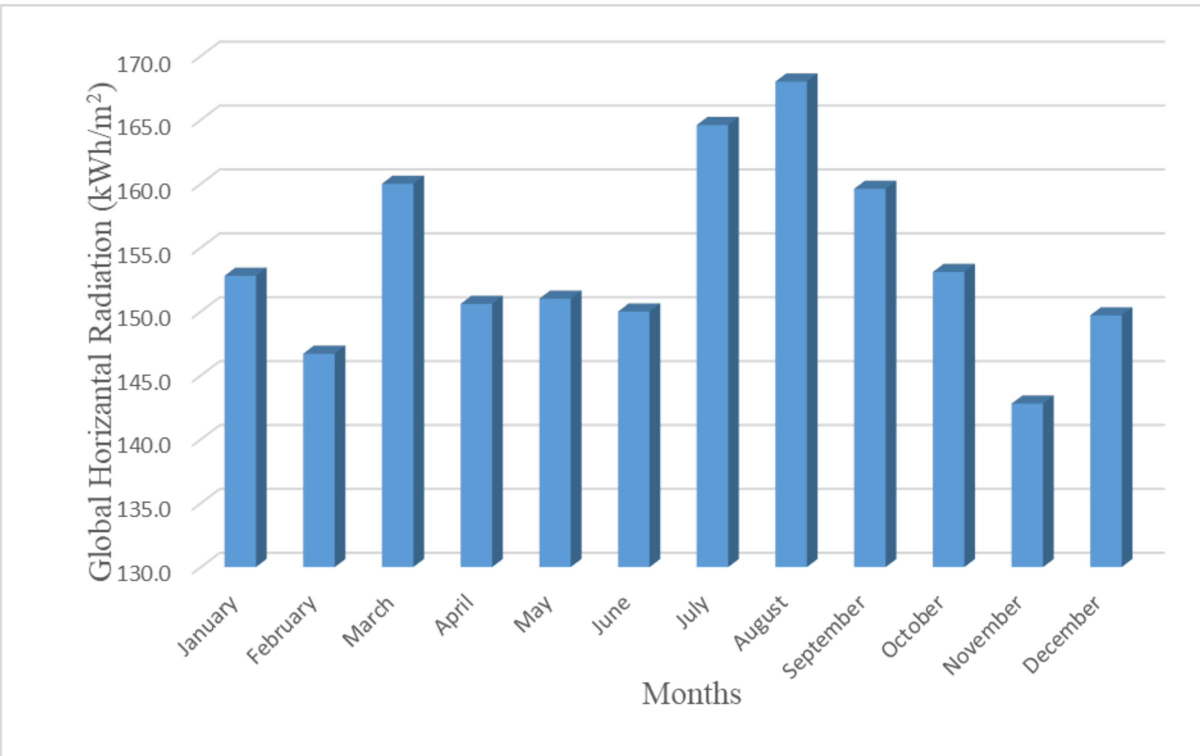

Figure 2: Seasonal average site radiation (Global radiation)

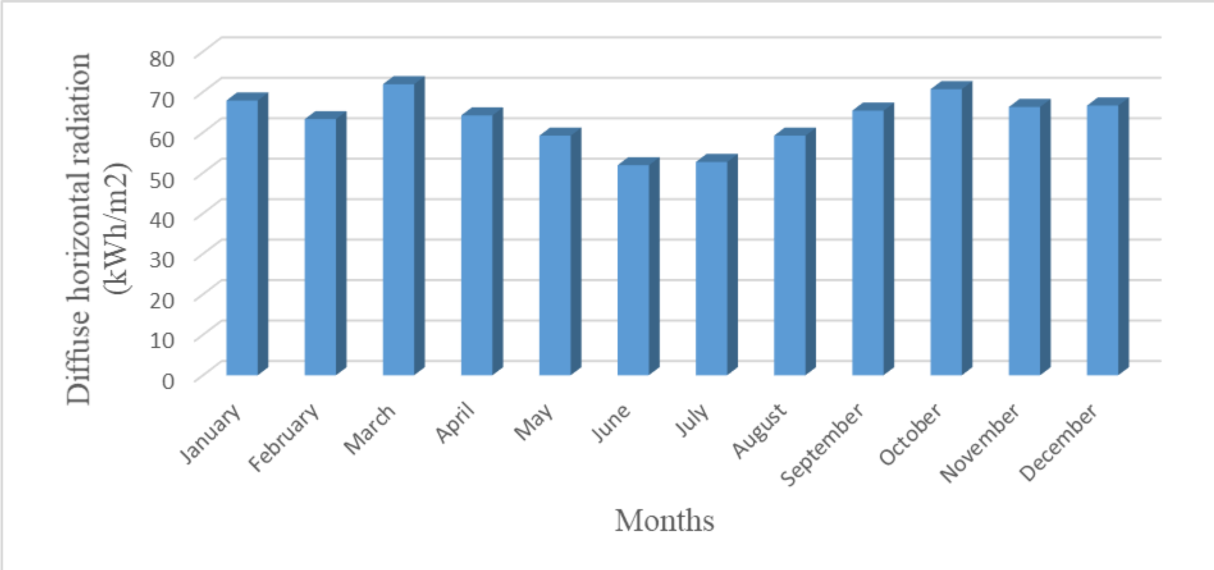

Figure 3: Seasonal average site radiation (Diffuse radiation)

5.3.3 Energy Consumption for Ruhango Provincial Hospital

The load assessment related to Ruhango provincial hospital was conducted by looking at the energy consumption during five recent consecutive years where the following is showing details related to the yearly energy consumption which increases concerning the increase in hospital services that are being provided to the nearest population. This consumption assessment includes the amount of power indicated on the bills provided by EUCL which is in charge of energy payment recovery and monitoring but the cost of fuel utilized when the power from the national grid was not available, was not computed. The hospital uses electricity to supply a variety of the available loads such as lamps, medical equipment, and other electrically powered materials. In case of power shortages, some medical equipment that is unable to operate highly affects the patients who are in critical conditions; which is the reason why the hospital needs a continuous power supply. Due to this, the hospital utilizes the UPSs on the very sensitive machines that may affect the life of patients when power is interrupted and then generators are utilized to supply the remaining materials of the hospital and to support the UPS for a short time of autonomy. The data relating to the energy consumption for Ruhango provincial hospital were recorded on basis of the financial year which starts in July of the year and ends on the 30th day of June in the following year. The table shown below provides detailed consumption and the cost associated with purchasing electricity.

Table 2: Summary of energy consumed by Ruhango provincial hospital and the corresponding cost within five years

Year	Energy consumed (kWh)	Unit price (Rwf/ kWh)	Amount (Rwf)
2016-2017	**118,652.84**	227	26,934,195
2017-2018	**117,766.76**	227	26,733,054
2018-2019	**127,035.77**	227	28,837,119
2019-2020	**117,604.17**	220	25,872,917
2020-2021	**124,784.60**	220	27,452,611
Total	**605,844.13**		**135,829,896.0**
Yearly average	**121,168.83**		**27,165,979.2**

5.4 Simulation

The economic feasibility of the solar PV system proposed in kinazi sector is performed and the results related to sizing of solar PV system components, the Levelized cost of electricity, life cycle assessment of solar PV installation, and other required factors were shown by using competent software simulations from the NREL. PVsyst 7.2.5 software provides the information required to design this project as well as judge its profitability.

6. Findings and Discussions

6.1. Introduction

The design process of PV power plants includes dimensioning, selection of solar PV panels, DC to AC converter, and transmission lines from the power control room to the national grid. Dimensioning of the equipment has a significant impact on the achievement of the goal set while designing a solar PV system. Under-sizing of the used equipment and materials may result in the poor power quality generated and dissatisfaction of the hospital. The power control equipment is also selected according to its size, cost, and efficiency. The Kinazi solar PV power plant can generate 4.5MWp. The estimated load for the hospital is averaged to 332kWh per day from five years of data related to the energy consumption of the hospital.

6.2 Minimum Technical Requirements

The minimum technical requirements for materials that are going to be considered while implementing this project have to be complying with those which RURA stipulates. Some requirements are related to the labeling of the solar PV module which must indicate the details like the short circuit current, open-circuit voltage, current at maximum power, voltage at maximum power, and the power rating at standard test conditions (STC). The solar modules conform to the following standards:

i) RS IEC 61215 Crystalline silicon terrestrial photovoltaic PV modules – design qualification and type approval

ii) RS IEC 61730 photovoltaic PV modules safety qualification –requirements for construction and requirements for testing. The bypass diodes are installed on each module to prevent hotspots in modules that may occur because a module can be shaded at a certain level of its available surface. The inverter which is going to be used in the system power conversion must have a warranty of at least five years while the efficiency ranges between 75% and 90%. The inverter certification, labeling requirements, and others were also provided.[15] The interconnection of the inverter output has to be set at a nominal line voltage of 400V and phase voltage of 230V with a maximum tolerance range of ±10%.

6.3 Nominal Frequency and Operating Frequency Range

Since the output power from this solar PV power is going to be injected into the national grid, the inverter responsible for converting DC to AC power is utilized and it has to provide the ac power at the nominal operating frequency of 50HZ. The frequency range should be lying between +6% and -6% (53HZ and 47Hz). Once the frequency value is beyond the allowed range, the protection relays at generation shall operate to shut down the plant after a delay time of 500ms.

6.4 Design Layout

The system is designed as shown in the following layout where the interaction of the main components is also shown. In most cases, the following components are utilized and sized effectively to increase their loading capability, enabled to generate the sufficient amount of power required by the customers.

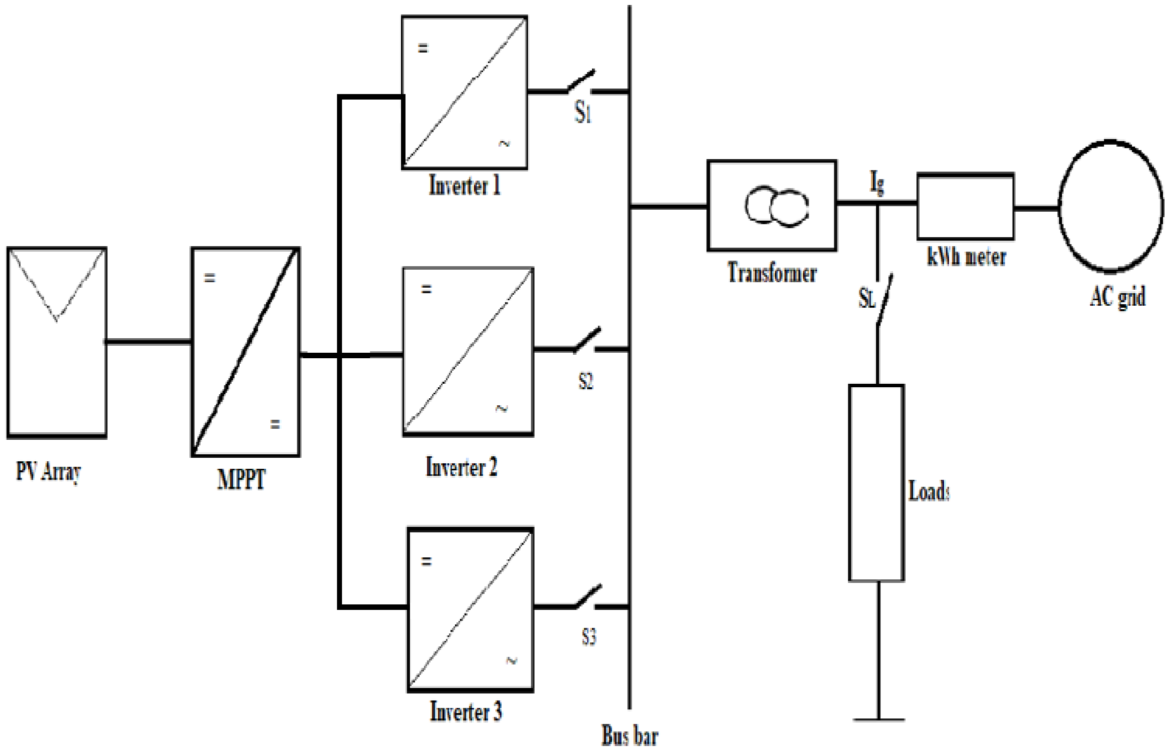

Figure 4: schematic diagram of the proposed PV system design

6.5 Description of the Proposed PV System Component

This system can operate as a grid-connected system or a standalone system. The above block diagram indicates the illustration of the block diagram.

PV Generator: this part consists of PV modules connected in series and parallel to meet the design requirements for controlling the power generated.

MPPT: **MPPT** or **Maximum Power Point Tracking** is the algorithm that is embedded in the charge controller system used to capture the maximum available solar radiation as well the maximum power from the PV module. When the PV module provides its maximum voltage, the corresponding power is known as the "maximum power point" (or peak power voltage). The maximum power for the PV module system depends on solar radiation, solar cell temperature, and ambient temperature. The maximum power point tracking is most effective under the following conditions:

- Cold weather, cloudy or hazy days: The PV module performs well when the temperature is cold and the maximum power point tracking system is used to extract the maximum power available.
- As far as the battery storage system is concerned for the PV system design if the battery is discharged: The maximum power point tracking system with its algorithm detects the state of battery charging status and extracts more current to charge the battery.

Inverter: The grid-connected inverter converts DC power from the PV array through the maximum point tracking (MPPT) into AC power which is suitable for the power that has to be injected into the grid.

Bus bar: A bus bar is a metallic bar in a switchgear panel used to carry electric power from incoming lines for feeders and distributes it to the outgoing lines of feeders. In simple terms, a bus bar is an electrical node where incoming and outgoing currents exchange. A single bus as shown in the figure below is utilized in this system and consists of several lines electrically connected with a few incoming and outgoing lines which are operating at the same voltage and frequencies. This bus bar construction can be made of copper or aluminum material.

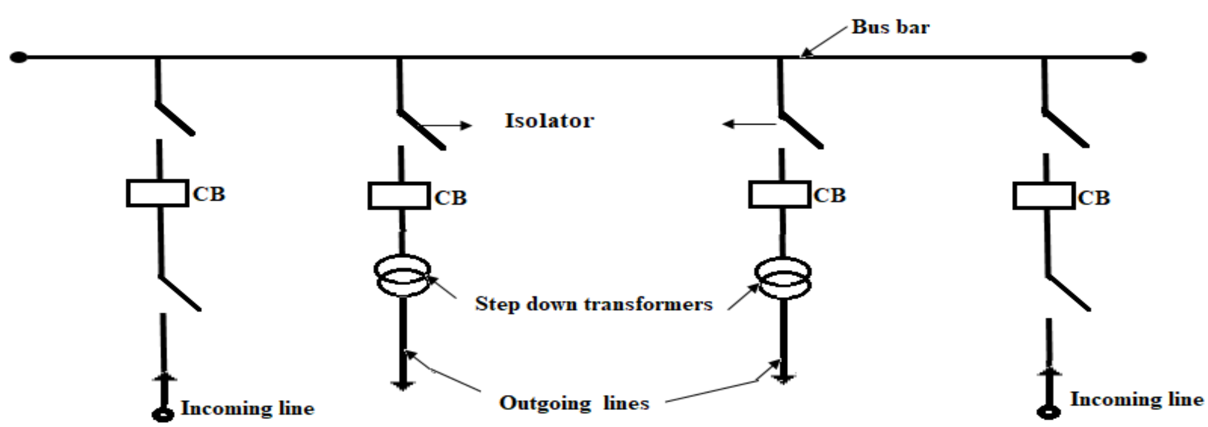

Figure 5: Single bus bar system

Transformer: is a static electrical machine that is used to transform power from one circuit to another at a constant frequency. Due to its construction without rotating parts, it is also known as a static machine. The step-down transformer which generally works on the principle of mutual induction is required in the designed system to provide power that is suitable for the available loads operating at low voltage.

Bidirectional kWh meter: This device is installed based on electricity regulations in Rwanda. it is responsible for counting the energy generated by the plant, energizing the load system, and the energy injected into the national grid from the PV array system. Based on the bidirectional meter readings, the hospital may pay or be paid by the energy utility company (Energy Utility Corporation Limited).

6.6 Design and Sizing of the PV System

6.6.1 Sizing of the System Components

All components of the solar PV system should be properly sized to meet the system design requirements, providing the maximum possible solar PV power generation concerning the available solar radiation.

$$I_L = \{I_{sc} + \alpha_i(T-25)\}\frac{G}{Gref} - I_{sat}\left(e^{\frac{qVD}{mNsKT}} - 1\right) - \frac{I_L R_S + V_L x^2}{Rp} \quad (5)$$

where I_s, I_d, I_p, and I_{sat} are the photocurrent, diode current, and saturation current at nominal PV standard tests condition (STC) (generally 25°C and 1000W/m^2) for temperature and irradiation, where I_s is highly affected by the two factors, the diode current of the PV cell, shunt current and the reverse saturation current of the solar panel, respectively. N_s indicates the number of cells connected in series, V_L is the thermal voltage that is equal to 25.7V at 25°C (298K) and m is the ideal factor of the diode (1-5 (V_L)). K is the Boltzmann constant (1.381×10^{-23} J/K) and q is the charge of the electron (1.6021×10^{-19}C). R_S and R_P are the solar module equivalent series and parallel resistance, respectively.[6][17]

From the result obtained by using the PVsyst 7.2.5 software, the PV array characteristics were adopted: Mono-crystalline silicon PV module manufactured by Solar World, model: 5BB Sun module Plus SW 300 mono, 20 modules in series and 750 strings in parallel, totaling to 15000 modules of 300Wp. V_{Mpp} and I_{Mpp} are 580V and 6998A respectively.

6.6.2 PV Output Power Estimation

The DC power generated from the PV system is mainly depending on several factors, like the maximum PV power extracted in PV arrays at standard test conditions (STC), the available solar radiation on the concerning site location, and the temperature of the cell. Such a simple model is represented in:

$$P_{PVout} = P_{PVpeak} X \left(\frac{G}{G_{ref}}\right) X \left(1 + K_T\left(T_c - T_{ref}\right)\right) \quad (6)$$

where P_{PVout} is the output power extracted from the PV array, P_{PVpeak} is the maximum available power of the PV array at STC, G is solar radiation in W/m^2, G_{ref} is solar radiation at STC amounting to 1000W/m^2, KT is the temperature coefficient of mono and polycrystalline Si cells amounting to (KT = -3.7×10^{-3} (1/° C)), T_{ref} is the temperature reference at standard test conditions which is equivalent to 25° C, and TC is the cell temperature calculated by using the empirical equation given below: [18]

TC = Tamb + 0.0256 × G,

where T_{amb} is the ambient temperature

6.7 DC to AC Inverter Sizing

The DC to AC inverter converts the DC voltage from the PV array or storage batteries to AC at the appropriate voltage level for consumption by the loads through some suitable techniques required for providing an output voltage and current waveform that is suitable for many applications. Inverters are usually replaced at least once within a period of 25-years after setting up a PV array system. With the present technology, inverters (smart inverters) allow two-way communication between the inverter and the electrical grid. They can balance the supply and the demand either automatically or through remote communication by the grid operators. This operating system of the grid inverter enables the utilities to reduce electricity costs, ensure grid stability of the system power generation, and reduce the likelihood of power shortages.

The inverter sizing operation must consider that all the loads may be turned on at the same time and run for a long time without any power shortage. This implies that most of the time that the inverter is running, it is operating at a smaller load than its rated load.[6] In the design of a solar PV system, the inverter size has a considerable impact on the overall electricity that is produced by the system. Three primary factors are to be taken into account when sizing or selecting an inverter:

i. The size of the solar array (minimum and maximum number of modules in series)

ii. The geography of the concerned location

iii. The site-specific conditions

The array to inverter ratio of the solar PV system is the DC rating of the solar array to the maximum Ac output of the inverter. Most of the installations have a ratio between 1.15 to 1.25 but the inverter manufacturer may give some other recommended ratios.

Inverter size = total load power x oversize factor where; oversize factor = 1.15

From the results obtained from the calculations made by the PVSyst 7.2.5 software, considering the available used area of 25150 m^2 with unlimited loads to the system, the output power of 4.5MWp is generated. While determining the size of the inverter suitable for the designed PV power production plant, 3 inverters of 1500kWac were manufactured by ABB and with Model: ULTRA 1500-TL-OUTD-2-US-690-M/S-DNVKEMA. The operating voltage ranges from 470 to 900V with a Pnom ratio (Array nominal installed power at STC)=1.0. Therefore, the total power from three units = 4,500 kWac

6.8 Estimation of the Electric Load

It is valuable to examine the energy required for the hospital and some neighboring citizens as they will be highly affected by the designed PV power system which will be interconnected to the national grid system. The energy demand from the hospital apparatus and some neighboring populations will be fed by the designed PV when the sun is providing enough solar radiation to generate the minimum required energy but whenever the plant fails to satisfy the electrical demand due to the low power generation from the PV power plant, the grid will immediately take over so that the life-related services provided by the hospital may not be affected. Therefore, the PV array and inverter sizes were determined based on the possible energy that may be generated from the system. From the data collected on-site, it has been found that the hospital has an average consumption of 332kWh per day.

6.9 Simulation Results

The grid-connection of the nonconventional energy resources are pollution-free resources and reliable technology is being increased to substitute the fossil fuels related to the present energy shortage, pollution of the environment, and the growth of the worldwide economy.

The simulation of PVSyst 7.2.5 software provides the required technical results for a 4.5MWp grid-connected PV system where the significant data such as the system balance (Global and horizontal radiation, Ambient temperature, global incident in collector plane, effective global, collector for IAM, and shading, array virtual energy at MPP, effective energy at the output of the array and the energy injected into the grid are given and very useful to the analysis of the system feasibility with advantage and challenges related to the installation of the proposed PV power plant design.[19]

6.9.1 Incident Energy

The incident energy is a major of the global horizontal irradiation, horizontal diffuse irradiation, ambient temperature, global incident in the collector plane, effective global corrected for IAM and shadings, effective energy at the array's output, energy injected into the grid, and the performance ratio. It is shown the site irradiance increases continuously from 6:00 AM and starts decreasing from around 2:30 PM and reaches its lowest value around 6:00 PM. This implies the plant is not generating any amount of power during the night and very early in the morning.

Table 3: Energy Balance and main results of the project

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh	E_Grid kWh	PR ratio
January	152.8	67.89	19.25	142.6	137.7	554358	538851	0.840
February	146.7	63.28	20.01	140.5	136.3	544021	528858	0.836
March	160.0	71.92	19.72	158.7	154.3	611964	594857	0.833
April	150.6	64.20	19.36	155.5	151.6	606589	589465	0.842
May	151.0	59.21	20.75	160.6	156.7	616699	599193	0.829
June	150.0	51.90	20.98	164.0	160.3	632790	614818	0.833
July	164.6	52.70	20.88	179.2	175.0	689853	670716	0.832
August	168.0	59.21	21.87	177.3	173.3	680363	661341	0.829
September	159.6	65.40	22.00	160.4	156.3	611325	593976	0.823
October	153.1	70.68	20.02	149.0	144.7	580389	564445	0.842
November	142.8	66.30	18.91	134.2	129.5	525810	511334	0.847
December	149.7	66.65	18.90	138.5	133.3	540424	525255	0.843
Year	1849.0	759.34	20.22	1860.5	1808.9	7194585	6993108	0.835

Legends: GlobHor Global horizontal irradiation

DiffHor Horizontal diffisue irradiation

T_Amb T amb.

GlobInc Global incident in coll. plane

GlobEff Effective Global, corr. For IAM and shadings

EArray Effective energy at the output of the array

E_Grid Energy injected into the grid

PR Performance Ratio

6.9.2 Energy Use

The overall energy injected into the grid is 6993 MWh per year. This is the sum of monthly energy generation which is slightly varying throughout the year, depending on different technical parameters. The energy generation is proportional to the global incident radiation as shown in the following figures.

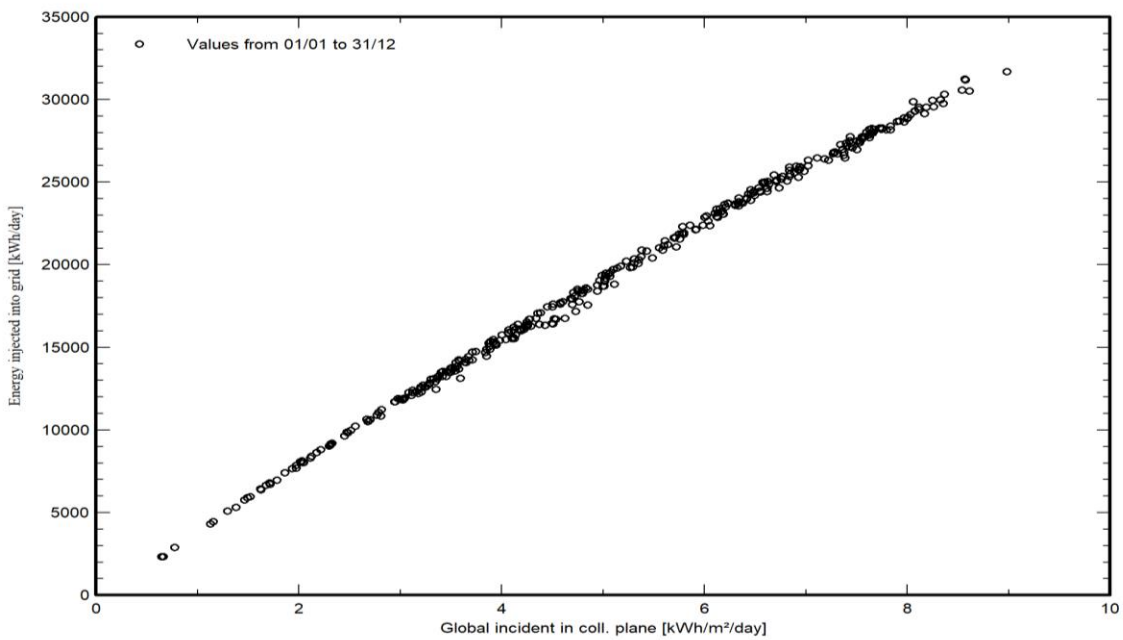

Figure 6: Energy injected into the national grid as a function of the global solar incident

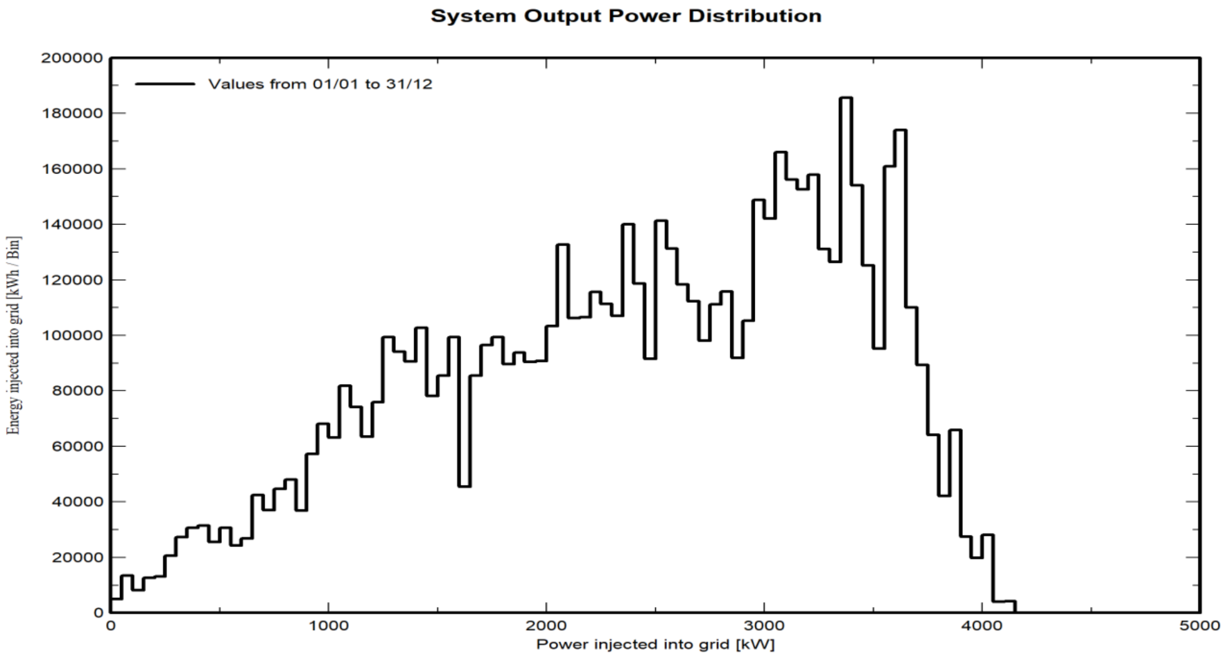

Figure 7: Power injected into the grid versus energy injected into the grid

Table 4: Monthly hourly sums for energy grid (MWh)

	0H	1H	2H	3H	4H	5H	6H	7H	8H	9H	10H	11H	12H	13H	14H	15H	16H	17H	18H	19H	20H	21H	22H	23H
January	0	0	0	0	0	0	1	21	41	61	73	72	69	68	57	44	26	6	0	0	0	0	0	0
February	0	0	0	0	0	0	0	19	41	59	73	77	71	61	51	41	27	8	0	0	0	0	0	0
March	0	0	0	0	0	0	1	23	45	62	73	74	80	76	67	52	32	9	0	0	0	0	0	0
April	0	0	0	0	0	0	2	28	49	65	72	78	80	72	59	49	30	5	0	0	0	0	0	0
May	0	0	0	0	0	0	6	31	52	62	76	82	81	73	62	46	26	2	0	0	0	0	0	0
June	0	0	0	0	0	0	2	30	50	66	77	81	78	79	68	51	31	3	0	0	0	0	0	0
July	0	0	0	0	0	0	1	29	52	72	84	83	87	84	76	57	35	10	0	0	0	0	0	0
August	0	0	0	0	0	0	1	29	53	72	83	86	88	82	71	54	32	9	0	0	0	0	0	0
September	0	0	0	0	0	0	7	32	53	69	79	76	76	70	60	46	24	1	0	0	0	0	0	0
October	0	0	0	0	0	0	10	33	53	68	79	73	71	66	55	37	19	0	0	0	0	0	0	0
November	0	0	0	0	0	0	8	29	47	63	72	63	63	62	50	35	18	0	0	0	0	0	0	0
December	0	0	0	0	0	0	5	25	44	59	69	70	71	64	56	39	21	2	0	0	0	0	0	0
Year	0	0	0	0	0	0	46	328	580	778	911	916	915	857	732	551	322	57	0	0	0	0	0	0

6.9.2 Performance Ratio

The performance ratio (PR) is measured output to nominal plant output for a given reporting period based on the system name-plate rating. It effectively indicates the performance of the plants at different locations. The performance ratio indicates the energy efficiency and the reliability of the plant. The factors like the temperature, soiling of module or sensors, irradiance, the efficiency of the module and inverter, solar technology, and recording period may influence the performance ratio. [20]

$$PR = \frac{Measured\ output\ (kWh)}{Rated\ \ output\ power\ for\ the\ plant\ \ (kWh)} \quad (1)$$

Important factors in PV performance

The most significant and direct impacts on PV performance are in-plane irradiance received by the PV array, the PV cell temperature, and the shading losses due to soiling or snow

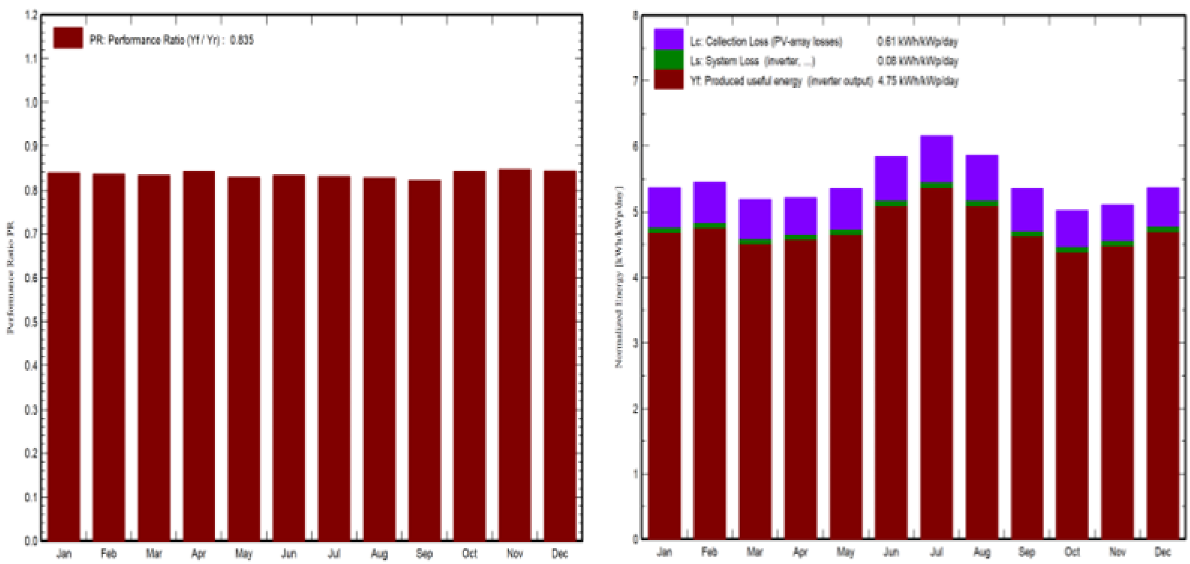

Figure 8: Performance ratio (PR) and normalized production per installed kWp

7. Analysis and Discussion

a) Technical Analysis

The performance ratio indicates the ratio between the output power measured from the inverter terminals and the power yield from the PV array. The percentage of energy lost in the generation process before it is injected into the national grid is shown in the following figure (fig.18).

Generally, the performance ratio value lies between 60% and 80%[19]. The figure indicates that a lot of losses that occur on the array may be caused by the operating temperature against 25^0C (STC), degradation of PV modules, irradiance level, or any other source. There are a considerable amount of losses from the inverter which may also be caused by different sources like shading and soiling, wiring, misalignment of the tracking system, and so on. As the figure below indicates, the array and inverter losses are 9.2% and 2.8%, respectively. It is also shown that more than 14% of the solar energy was not converted into useful energy due to the array and inverter losses that occur before the injection of energy into the grid.

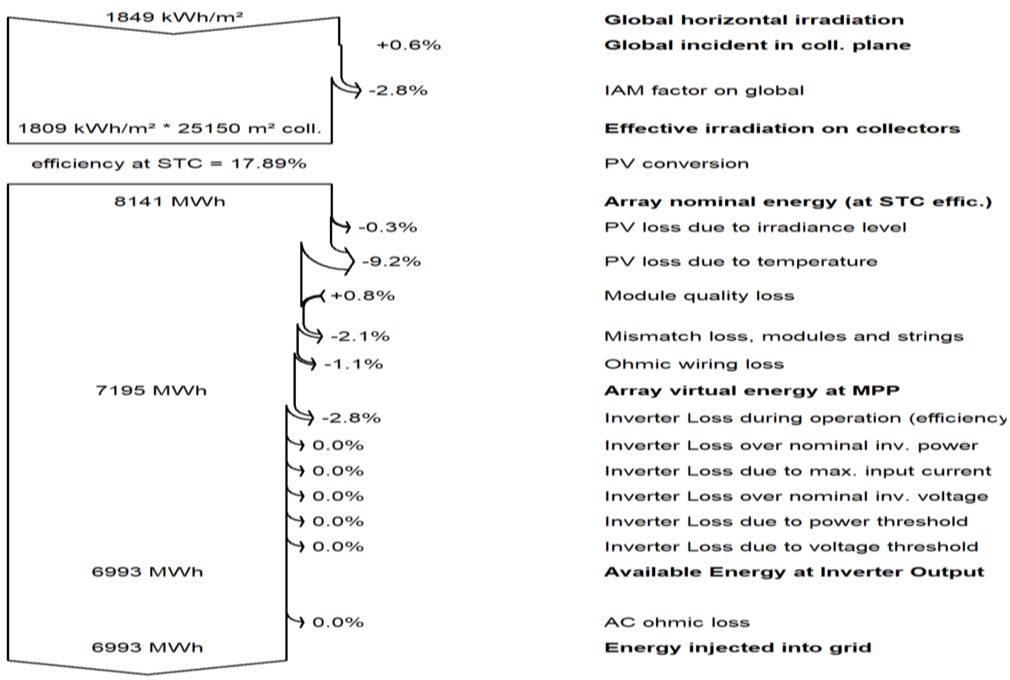

Figure 9: Loss diagram of the PV system over the year

b) Economic Evaluation

For the economic evaluation of this project design, three main factors are used to evaluate the profitability of the project:

Net Present Value: The net present value of an investment project at time t = 0 is very sensitive to the project attractiveness. The calculation of the NPV internalizes all possible costs and benefits; its value has to be positive for a project to be profitable and acceptable. The higher the NPV value, the more the project is profitable and when NPV is negative, the project is not profitable and it is not advisable to invest in it.[21] the obtained results from the simulation show a profitable project as the value of the NPV is positive and very attractive to the investor.

$$NPV = -Co + \sum_{t=0}^{T}(R_t - I_t)q^{-t} + S \text{ X } q^{-T} \quad \text{with } q^{-t} = \left(1 + \frac{i}{100}\right)^{-t} \qquad (2)$$

Where Co is the investment cost at t time t=0

T: the lifetime of the project in years

Rt: the return in period t

I_t: the investment in period t

q^{-t}: the discount factor

i: the discount rate

S: the salvage value

Internal rate of return (IRR):

The internal rate of return indicates the interest rate the NPV will be equivalent to zero which indicates the achievable interest tied up in the initial cost. The following expression is useful for the analysis of the project [21]

$$0 = -I_0 + \sum_{t=1}^{T} R_t \left(1 + \frac{IRR}{100}\right)^{-t} + S\left(1 + \frac{IRR}{100}\right).^{-t} \qquad (3)$$

Where:

Discounted payback period (Dpp):

The discounted payback period indicates how long the project takes to recoup the corresponding total investment considering the present value of projected cash flows from the project. The short discounted payback period indicates that the investment project will generate cash flows to cover the initial cost in a short period. The discounted payback period should be less than the project service life.[21] the simulation result shows that the payback period for this project is 11.8 years.

$$Dpp = \frac{I_0}{\left(\sum_{t=0}^{T}(R_t - I_t)/T\right)} \tag{4}$$

The following table shows detailed economic results related to implementing the project in the Ruhango district. The electricity sales, running costs, depreciation allowance, taxable income, after-tax profit, and cumulative profit are given on yearly basis.

Table 5: Table showing the details on economic results for the project in USD

	Electricity sale	Run. costs	Deprec. allow.	Taxable income	Taxes	After-tax profit	Cumul. profit	% amorti.
2023	839'173	10'600	297'360	531'213	0	828'573	-5'656'303	11.9%
2024	847'565	11'448	283'087	553'030	0	836'117	-4'939'467	23.1%
2025	855'957	12'364	269'499	574'094	0	843'593	-4'269'796	33.5%
2026	864'348	13'353	256'563	594'433	0	850'995	-3'644'289	43.3%
2027	872'740	14'421	244'248	614'071	0	858'319	-3'060'132	52.4%
2028	881'132	15'575	242'212	623'345	0	865'557	-2'514'684	60.9%
2029	889'523	16'821	242'212	630'490	0	872'703	-2'005'471	68.8%
2030	897'915	18'167	242'212	637'536	0	879'749	-1'530'170	76.2%
2031	906'307	19'620	242'212	644'475	0	886'687	-1'086'606	83.1%
2032	914'699	21'189	242'212	651'297	0	893'509	-672'738	89.5%
2033	923'090	22'885	242'212	657'994	0	900'206	-286'655	95.5%
2034	931'482	24'715	242'212	664'554	0	906'767	73'434	101.1%
2035	939'874	26'693	242'212	670'969	0	913'181	409'209	106.4%
2036	948'266	28'828	242'212	677'225	0	919'438	722'242	111.2%
2037	956'657	31'134	242'212	683'311	0	925'523	1'014'005	115.8%
2038	965'049	33'625	242'212	689'212	0	931'424	1'285'879	120.0%
2039	973'441	36'315	242'212	694'914	0	937'126	1'539'155	124.0%
2040	981'832	39'220	242'212	700'400	0	942'612	1'775'043	127.6%
2041	990'224	42'358	242'212	705'654	0	947'866	1'994'675	131.1%
2042	998'616	45'746	242'212	710'657	0	952'869	2'199'111	134.2%
2043	1'007'008	49'406	242'212	715'389	0	957'602	2'389'344	137.2%
2044	1'015'399	53'359	242'212	719'829	0	962'041	2'566'303	140.0%
2045	1'023'791	57'627	242'212	723'952	0	966'164	2'730'855	142.5%
2046	1'032'183	62'238	242'212	727'733	0	969'945	2'883'815	144.9%
2047	1'040'575	67'217	242'212	731'146	0	973'358	3'025'942	147.1%
Total	**23'496'845**	**774'923**	**6'195'000**	**16'526'922**	**0**	**22'721'922**	**3'025'942**	**147.1%**

c) Environmental Impacts

The rooftop mounted solar PV power plant at Ruhango provincial hospital will contribute to significant environmental benefits compared to the use of conventional resources. The solar PV power generation technology provides a considerable reduction of CO_2 emissions and the quality power yields from the plant are provided to the population which improves their living standards. Different terrestrial researchers have found that the reduction in CO_2 emission obeys the ratio of 0.7kg CO_2/kWh generated. Therefore with this amount of energy generated from Ruhango provincial hospital, a considerable amount of CO_2 emission will be saved every year.[22]

8. Conclusion and recommendations

8.1. Conclusion

The study analysis of 4.5MWp solar PV power production is discussed along with the case study. The selected site is among the Rwandan territory which is hit by more than the minimum solar radiation required for effective solar PV power generation; Ruhango provincial hospital receives enough solar radiation that yields 6993 MWh per year, and based on the generating capacity of the site, the plant may contribute a lot to the increase of national installed capacity with reduced environmental impact. The maximum amount of incident radiation hits the proposed site from March to September while in February and November, the radiation is not very impressive. The daily site irradiance increases continuously from 6:00 AM and starts decreasing from around 2:30 PM and reaches its lowest value around 6:00 PM.

The selection of the appropriate system components and description of their corresponding behavior was followed by modeling PVSyst 7.2.5 software which supported a lot in techno-economic analysis and feasibility of the plant, assessing the economical and reliability of the plant, supplying the quality power to the hospital and neighboring citizens. The initial investment for this plant is high but the energy generated and money that can be saved within few years after its implementation, motivate the implementation of the studied project.

Solar PV systems are globally known as the best choice for electric power generation. The research has shown that solar is abundant in more than 70% of Rwandan territory, But still, the exploitation of solar energy resources in Rwanda is not being done sufficiently to alleviate the energy shortages that occur in a country like Rwanda which strives for becoming a middle-income country.

8.2 Recommendations

The research done shows the profitability and feasibility of the rooftop mounted solar PV power plant intended to be implemented where Ruhango provincial hospital is located. It has been shown that the plant will be generating only when the solar radiation is available, the power generation increases in the morning and starts decreasing in the afternoon until the plant shuts down when the minimum required irradiance is not available at the plant site. So, it is recommended for future researchers, to consider the feasibility of energy storage for this plant to supply the hospital and neighboring citizens autonomously.

The techno-economic analysis done in this research has shown that Ruhango provincial hospital location is suitable for PV power systems and the hourly and yearly energy generation results are very attractive to investors. In addition to this, the design calculations show that the investment made for this grid-connected solar PV power plant can be recouped in a few years after its implementation and a considerable amount of money spent by the hospital consumption for monthly electricity billing can be saved. So It is recommended to the management of the hospital and Ruhango district, to consider the positive impact that can be benefited from the implementation of this project for the entire country and avail the funds for investment in it.

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