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EXCELLENCE IN ENERGY FOR
SUSTAINABLE DEVELOPMENT

OPTIMUM DESIGN OF A GRID CONNECTED HYBRID SOLAR PV-RUGEZI RUN OF
THE RIVER HYDRO POWER PLANT SYSTEM FOR POWER SHORTAGE MITIGATION

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in

Electrical Power Systems

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KIGALI-RWANDA

DECLARATION

I hereby declare that this thesis is a result of my own work and has not been submitted to the University of Rwanda or any other institution under consideration for a degree.

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APPROVAL SHEET

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

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A handwritten signature in black ink, appearing to read 'BIKORIMANA JMV', is written over a light gray rectangular background.

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Thanks to almighty God who has been leading my steps in this research. I am thank full for my family for encouraging me during my studies. I would like to express my sincere thanks to the supervisor Dr. BIKORIMANA JMV for his guidance and advice in this research journey. Thanks again to Rwanda Mountain Tea Company for giving us the right for data collection at Rugezi run of the river hydro power plant.

ABSTRACT

As the global energy demand is increasing rapidly all over the world, hybrid systems of renewable energy sources provide reliable, clean and cost-effective electrical energy. The hybrid system formed by solar PV and hydro power plant is the best choice in Rwanda the country with high potential of hydro resources and solar irradiance.

In this research the hydro logical data with the corresponding power produced in different three consecutive years 2020,2021,2022 were collected at Rugezi hydropower plant which really helped to identify the existed highest power shortage, this highest power shortage was 1850kW and occurred in August 2020 and this is the basis of the designed solar PV power plant. The minimum power produced at Rugezi hydro power plant corresponding to that highest power shortage was 822kW. The designed solar PV power plant to mitigate the power shortage was combined with Rugezi hydro power plant so that the power generated by that formed hybrid system is always equivalent to the installed capacity of Rugezi hydro power plant. During this design the Musebeya site nearest water intake of Rugezi hydro power plant was selected as the best site for solar PV power plant installation ,the yearly average solar irradiance of the selected site is 4.71kWh/day .The installed capacity of the designed solar PV is 2000kWp and the output of the inverter is 1900kWac which is capable to mitigate the power shortage of 1850kWac.The PVsyst 7.3 software and PVsol software were used to design solar PV power plant and Homer pro was used to combine solar PV and hydro power plant so that they form hybrid system ,ETAP software was used for drawing the single line diagram of the hybrid system whereas Matlab software was used for linear programming of the hybrid system. Based on the hybrid system optimization it was found that one generating unit of Rugezi run of the river hydro power plant must be in operation and works in parallel with solar power plant during dry seasons for 1850kWac power shortage mitigation. As recommendation, Rwanda Mountain Tea Ltd the owner of Rugezi hydro power plant should implement this project because this will maximize their profit as independent power producers and mitigate the power shortage which occurs at Rugezi hydro power plant, this hybrid system will increase the country installed capacity and will contribute to carbon emission reduction once it is implemented.

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LIST OF ACRONYMS AND ABBREVIATIONS

HPP: Hydro power plant

LCOE: Levelized cost of energy

PV: Photovoltaic

REG: Rwanda energy group

RMT: Rwanda Mountain Tea

NLP: Nonlinear programming

MILP: Mixed integer linear programming

LP: Linear programming

GA: Genetic algorithm

MPPT: Maximum power point tracking

ANN: Artificial neural network

FL: Fuzzy logic

SHP: Small hydro power plant

MLP: Multilayer perceptron

PSO: Particle swarm optimization

ABC: Artificial bee colony

kWp: kilo watt peak

Wt:weight

P_{\min} :minimum power

P_{\max} :maximum power

η_{turb} : Turbine efficiency

η_{gen} :Generator efficiency

Wg:Power of generating unit

Ypv:number of solar PV modules

Xg:number of generating units

η_{all} :Overall efficiency

USD:United states dollars

kVA:kilovolt-ampere

GWh:Gigawatt-hours

kWh:kilowatt-hours

UN:united nations

EU:European union

δ : Water density

g: Acceleration due to gravity

Hn: Net head

Q(t): Water flowrate

AC: Alternating current

DC: Direct current

kWh: kilowatt –hour

NPV: Net present value

IRR: Internal rate of return

ROI: Return on investment

Wp: peak power rating for one solar PV module

CHAPTER ONE: INTRODUCTION

1.1 BACK GROUND

In an effort to decrease diesel power plants, the Rwandan government has been investing in hydroelectric projects. Present hydroelectric facilities account for 39% of the nation's installed capacity[1]. Run-of-the-river hydropower plants make up a portion of the smaller power plants; which depends on whether conditions among which Rugezi hydro power plant is included.

Rugezi run of the river hydropower plant is situated in BURERA district, Butaro Sector specifically on Rusumo tributary. During the wet seasons, the Rusumo tributary, which connects the Rugezi Wetlands to Lake Burera, flows at a rate of two cubic meters per second[2]. As water flowrate is highly reduced during dry seasons because there is no water storage or water reservoir this reduces the electrical power generated and the owner of this hydropower plant fails to have enough energy to be sold on national electrical grid.

Rugezi run of the river hydropower plant has installed capacity of 2.6MW and owner of this hydropower plant is Rwanda Mountain Tea ltd which sells the electrical energy generated to Rwanda energy group[3] .

The figure 1.1 below shows the seasonal variation of water flowrate at Rugezi hydropower plant in three consecutive years.

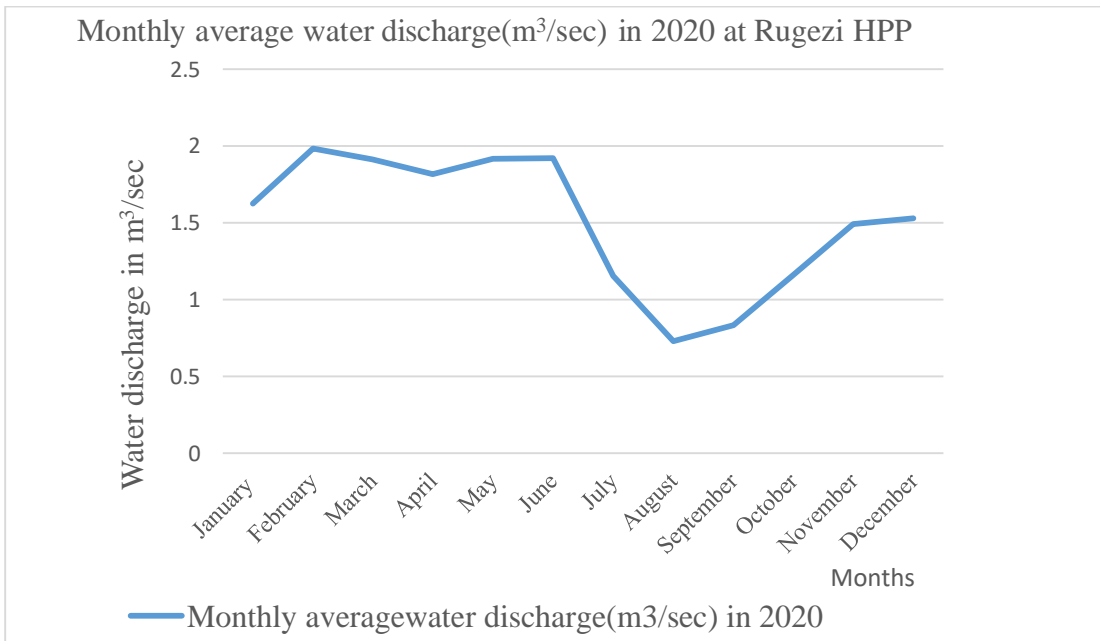
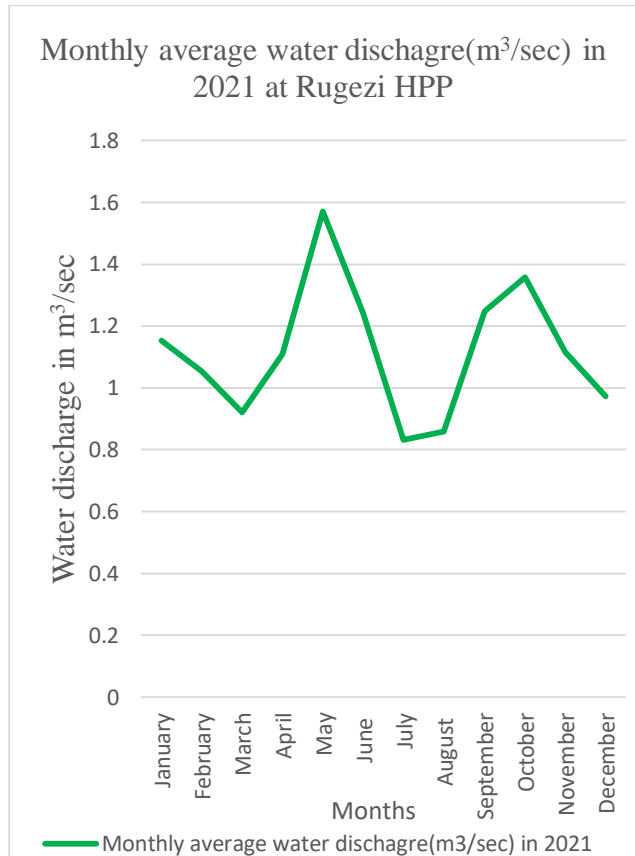
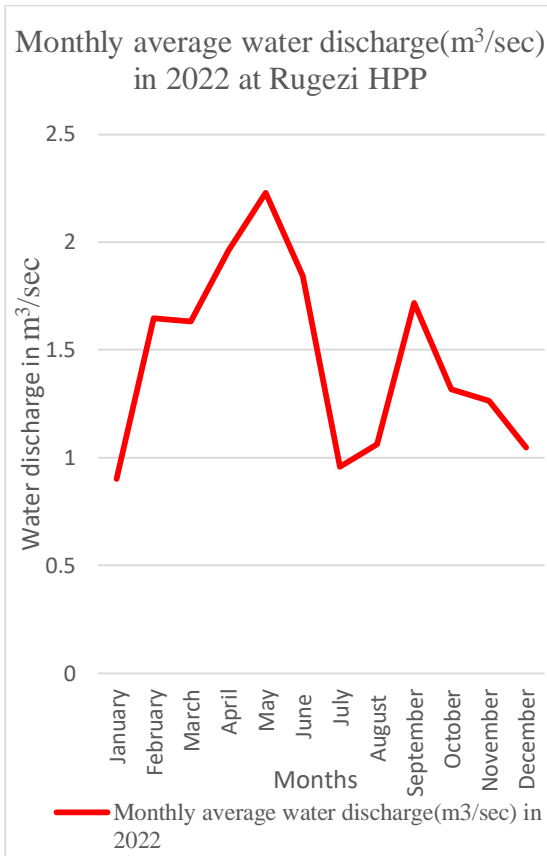


Figure 1. 1 Seasonal variation of water flowrate at Rugezi HPP in 2020,2021,2022

When it rains, it is more difficult to generate electricity using solar energy. While solar energy is widely available during the peak summer months, it is more efficient when electricity is generated utilizing hydro energy during the rainy periods. In a hybrid power system, two or more different types of generation sources are combined to produce electricity [4]. Hence, the hybrid system of hydro power plant and solar PV, produce the continuous power flow in the national grid. During the summer seasons, the hydro system is unplugged and the grid is supplied with electricity by the grid-connected solar system. In rainy days the hydro system injects the power into the grid, and solar system is disconnected. Grid-connected hydro and solar installations can supply electricity to the grid during other seasons. Therefore, developing this hybrid system to provide the grid with continuous electricity is a wise decision[5].

1.2. PROBLEM STATEMENT

The entire stream's water flow is permitted to travel through the turbine in run-of-river hydropower plants in order to generate electricity. When water is available, the plant uses it. Since the water flow rate in the river varies seasonally, more electricity can be produced during the rainy seasons than the dry ones.

Run-of-the-river power plants utilize the upstream natural flow of water in rivers. Consequently, these plants are less adaptable than hydroelectric facilities with sizable reservoirs as their ability to produce energy is dependent upon the river's water level. Because of this particularity, the energy produced is proportionate to the input of water, which explains why these hydropower plants produce varying amounts of power year-round.

Rugezi run of the river hydro power plant is among the hydro power plants which are highly affected by the seasonal variation of water flowrate where by during dry seasons the minimum power is produced similarly during the rainy seasons the power production is maximum. As the energy produced at Rugezi hydro power plant is directly sold to the national electrical grid, during the dry periods the Rwanda Mountain Tea company the owner of Rugezi hydropower plant does not have enough energy to be sold to the utility grid this affects the yearly profit of the business and reduces the installed capacity of the country.

Based on these identified problems the solar PV power plant is designed to be working in parallel with Rugezi hydro power plant so that they form hybrid system which is always capable of providing the maximum continuous power and increases the installed capacity of the country in line with the reduction of carbon emission in environment as they are renewable energy sources. In Rwanda, where energy consumption is rising quickly, these hybrid system technologies are not yet effectively applied.

1.3 OBJECTIVES

1.3.1 Main objective

The main objective of the present study is the Optimum design of a Grid connected hybrid solar PV-Rugezi run of the river hydropower plant system for power shortage mitigation.

3.1.2. Specific objectives

The following are the specific objectives of this research:

- Estimation of power shortage during sunny periods at Rugezi hydro power plant
- Site selection of the required solar PV power plant to be combined with Rugezi hydro power plant so that they make hybrid system.
- Sizing the required solar PV power plant for power shortage mitigation during sunny periods
- Economic analysis of the sized solar PV power plant
- Modelling and optimization of a grid connected hybrid system of solar PV- Rugezi hydro power plant.

1.5. SCOPE OF THE RESEARCH

This research is focused on design and simulation of hybrid system of solar PV- small hydro power plant case study of Rugezi grid tied small hydropower plant of installed capacity of 2.672MW the hydro power plant which is really facing problems of power deficiency caused by a direct water flow rate reduction in the river.

1.6 EXPECTED OUTCOMES AND SIGNIFICANCE OF THE STUDY

1.6.1 Expected outcomes

Expected outcome of this research is to get the optimized hybrid system of Rugezi hydro power plant and solar power plant which mitigate the occurred power shortage.

1.6.2 Significance of the study

This research contributes to the nation's expanded installed capacity and steady power production. The owner of Rugezi hydropower plant has enough electrical energy to be sold to the utility company which increases the yearly profit of the RMT company and the utility company REG buys this energy produced by the hybrid system at low cost. As this hybrid system is a combination of renewable energy sources there is a contribution to net zero carbon emission of UN program. The designed hybrid system contributes to the reliability of power and this is again the integration of renewable energy technologies in national grid.

1.7 THESIS OUTLINE

This thesis consists of six main chapters which are divided as follows:

Chapter one is the introduction of the whole thesis and this chapter has different subchapters which are as follows: Back ground of the study, problem statement ,objectives (main objective and specific objectives), Significance of the study ,Scope of the research,expected outcomes and thesis outline.

Chapter two is the literature review on grid connected solar PV -hydropower plant .This chapter has introduction about hybrid systems and related published works ,it shows again the description of main parts of hybrid solar PV-hydropower plants including hydropower plant and solar PV power plant. In this literature review different types of optimization are discussed.

Chapter three is the methodology used to achieve the research objectives this chapter consists of the following parts: Research design, data collection, methodology used for modelling the solar PV/hydro power plant hybrid system, tools used to simulate the grid connected hydro/solar PV hybrid system and the way of analyzing simulation results of that hybrid system with economic analysis.

Chapter four is the design and simulation of the hybrid system the chapter consists of the design of solar photo voltaic part, modelling part which is optimization mathematical models formulation and simulation models elaboration for hybrid system, levelized cost, payback period and the net present value calculation for solar photo voltaic system.

Chapter five is the results and discussion which is mainly the simulation results analysis

Chapter six is the conclusion and recommendation this include recommendations for future works.

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

The global challenge of providing reliable, clean and cost-effective energy is one of the major challenges which the world is facing with this century. The renewable energy sources are considered to be the most important and most effective solution for the future [6]. The hybrid system of renewable energy sources came as solution to produce reliable and cost effective energy.

A hybrid energy system, also known as a hybrid power system, often combines two or more renewable energy sources to improve system efficiency and improve energy supply balance. Hybrid energy systems combine two or more forms of energy generation, storage, or end-use technologies [7]. Because hydro and solar energy resources complement each other seasonally, hybrid power generation using both can be an alternate source. Photovoltaic power plants can supplement hydropower plants during dry spells[8].

The use of micro hydro and hybrid solar systems has increased recently for a variety of reasons, including cost and environmental concerns[9].

2.2 Related works

Emile NIRINGIYIMANA et al[10]in their research entitled “Feasibility Study of a Hybrid PV/Hydro System for Remote Area Electrification in Rwanda” their case study was mutobo micro hydro power plant in MUSANZE district and they aimed to optimize the mutobo micro hydro and solar pv hybrid system to increase the number of homes accessing electricity in MUSANZE district. MATLAB/Simulink was used for the construction and simulation of the hybrid system model, and data from the National Meteorological Agency, Rwanda Energy Group, and Mutobo micro hydropower station were utilized to evaluate solar energy potentials. It was discovered that hybrid solar PV and hydro systems are workable and significantly lessen the impact of power shortages in isolated locations where grid extension is not practical.

John Vourdoubas [11]in his research entitled “Integration of Floating Solar Photovoltaic Systems with hydropower plants in Greece” examined the viability and potential of putting up

floating solar power systems in Greece's current hydroelectric facilities. The nominal power of these photovoltaics, which can be installed in their water reservoirs and cover 10% of their water surface, is 3,861MWp. The annual electrical energy generated is 5212.35GWh, which corresponds to 10.04% of the country's annual energy demand. These data were obtained by estimating the solar PV systems that can be installed in the water reservoirs of 24 hydropower plants using their characteristics. More than 20% was added to the hybrid solar/hydro system's capacity factor. According to the research, Greece's hydropower plants can accommodate floating photovoltaic systems in their water reservoirs. These systems have the potential to produce a sizable amount of green electricity and offer numerous environmental advantages. The national and EU targets for net zero carbon emissions by 2050 can be met in part by this solar energy system and hydropower systems.

Getnet Zewde Somano et al[12] in their research entitled “Design and Modelling of Hybrid PV-Micro Hydro Power Generation Case Study Jimma Zone” created and modeled the MenkoToli River in Ethiopia's off-grid hybrid micro-hydropower system using solar photovoltaics. The river's average yearly flow rate is 1.131 m³/s. HOMER software had been used for modeling optimized result of the hybrid power generation system. 500 families with a combined yearly consumption of 31,911 kWh are deemed under studied. The elementary school and clinic's electricity loads were included in the study. 10kW PV, 14kW hydro, 14kW converter, and 32 battery strings were chosen as the best option for powering MenkoToli in Ethiopia using the HOMER software's optimization results. This option had an initial capital cost of \$55,200, a total net present cost of \$76,128 and a unit cost of \$0.045. In the study all combinations of hybrid sources for the HOMER software have been observed for cost effective design.

Dariusz Borkowski et al [13]in their research entitled “ Run-of-the-River Hydro-PV Battery Hybrid System as an Energy Supplier for Local Loads” This study examined a hybrid system of run-of-the-river small hydro power plants (SHPs), PV systems, and batteries for remote zone load supply. Low-power, low-head, speed- varying operation techniques were examined. This work suggested a particular run-of-the-river HPP steady-state model that can be used to examine energy output under different hydrological conditions. The MLP of a neural network was used to evaluate the water turbines efficiency. The estimates presented here, based on an actual SHP with a 150 kilowatts capacity, demonstrate that using a simple technique can lead to a forty three

percent overestimation of the energy produced. Furthermore, a year-long examination of a hybrid system's performance using actual river flow data showed that the energy balance outcomes were significantly impacted by the flow averaging time.

2.3 Literature gap

Researchers in [10] worked on feasibility study of a hybrid PVs/hydro system for remote area electrification in Rwanda case study of Mutobo micro hydropower plant however the behaviors of the run of the river hydropower plant were not considered, the modeled hybrid system was standalone, there was no calculations of levelized cost, NPV, ROI and payback period of that hybrid system and the calculations about the required solar PVs were not determined.

Researchers in [11] investigated the possibility and the potential of installing floating photovoltaic systems in the existing hydropower plants and estimated solar PV systems which can be installed in hydro power water reservoirs, however, they did not account for run-of-river hydropower facilities without reservoirs or dams, nor did they compute the cost of installing solar photovoltaic cells in water reservoirs or the hybrid system's levelized cost.

Researchers in [12] modeled and optimized the hybrid micro hydropower plant –solar plant. Nevertheless, the modeled system was a standalone hybrid system.

Researchers in [13] modeled hybrid system of SHPs, photovoltaic solar plant, and battery storage to supply loads in remote locations, However, they did not provide the precise number of solar PVs needed or the area covered by solar PVs close to the run-of-the-river HPP. They also neglected to include the cost of the hybrid system's installation, operation, and energy production per unit.

2.4 A grid connected solar PV-hydro power plant

A grid connected combination of Solar/hydro power plants is an alternative source of energy due to the seasonal complementarity between them. When tied to the grid, solar power plants can take the place of hydropower plants during dry spells to boost electricity production and stabilize the power system [14],[8]. Low-cost electrical energy is produced by the combined solar-hydropower system, which also increases the penetration of renewable energy sources into the utility grid [14].

2.5 Hydro power plant

Water moving from higher to lower elevations provides energy for hydropower, a renewable energy source. Hydropower plants generate electrical energy by fully using the potential energy of water. Out of all the known energy sources, hydropower has one of the highest conversion efficiencies. One of the greenest ways to generate electricity is by using the potential energy contained in stored water. Hydropower plants are a versatile source of electricity and may generate electricity at a comparatively low cost [15],[16].

Weight available in the water stream per second is given by equation (2.1)

$$(Wt) = QX\delta X g \quad (2.1)$$

Hydraulic power is thus a naturally available renewable energy source which is given by equation (2.2)

$$P = QX\delta X gxH \quad (2.2)$$

Electrical power generated by hydro power plant is given by equation (2.3)

$$P = QX\delta X gxHx\eta_{all} \quad (2.3)$$

Where Q: water discharge in m³ /s, δ : Water density in 1000kg/m³, H: Water head in m, g: acceleration due to gravity in m/s² and η_{all} : overall efficiency of hydroelectric power plant[17].

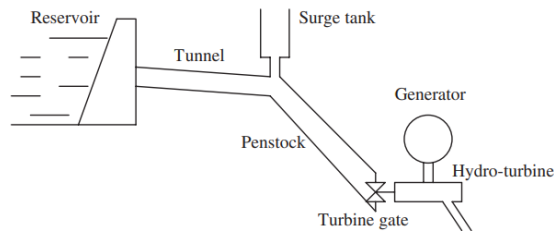


Figure 2. 1 Main components of hydropower plant[18].

Dam: A dam is a type of barrier that produces water head and stores water. Rock fill, concrete, or stone masonry are used to build dams.

Spillways: The river flow occasionally surpasses the reservoir's storage capacity. A situation like this occurs when the catchment area has a lot of rainfall. Spillways are utilized to release excess water from the storage reservoir into the river on the dam's downstream side. On top of the dam, concrete piers serve as the construction site for spillways. Between each of these piers are gates that, when opened, allow excess water to be released over the dam's crest[15].

Surge tank: A surge tank is a small, open-topped tank where the water level increases or falls to lessen conduit pressure swings. A surge tank is located near the beginning of the conduit.

Penstocks: Penstocks are open or closed conduits which carry water to the turbines. They are generally made of reinforced concrete or steel.

Water turbines: To transform the energy of falling water into mechanical energy, water turbines are utilized.

Generator: A generator is situated in the power house and is mechanically connected to the turbine shaft. The rotating turbine is the prime mover of generator, then this generator produces electricity which is stepped up by power transformer and then power is transmitted through transmission lines[15].

2.5.1 Types of hydro-power plants

- ❖ **Conventional plants:** Conventional plants utilize the energy that is stored in dammed water. The water's head and volume determine how much energy is extracted. Water head is the height of the water in a reservoir divided by the level of water outflow[16].
- ❖ **Pumped storage plant:** A second reservoir is situated close to the turbine's output in a pumped storage plant. Water is pumped into the upper reservoir from the lower reservoir when there is less demand for electrical energy. This is to make sure that there is enough water in the main reservoir to accommodate peak loads. [16]. The figure 2.2 shows the typical pumped storage power plant.

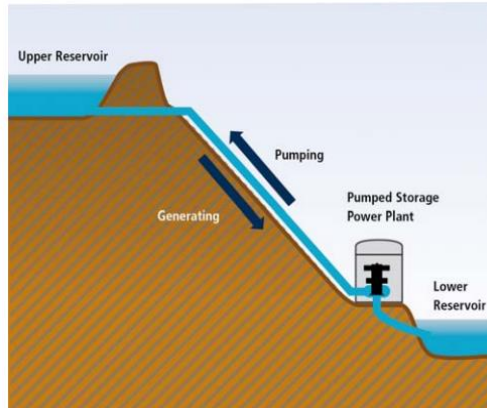


Figure 2. 2 Typical pumped storage hydropower plant [16].

- ❖ **Run-of-river hydro power plant:** There is no reservoir in this kind of plant because no dam is built. A penstock or canal directs a portion of the river to the turbine. Therefore, the generating may only use the water that flows from the river. Additionally, because there is no storage, any excess water is wasted[16]. Because the production of energy from these facilities is contingent upon the availability of water in the river, they are less adaptable than hydropower stations with sizable reservoirs. Because of this unique feature, the energy produced is proportionate to the volume of water entering the plant. This explains why run-of-river hydropower facilities produce varying amounts of power year-round[19]. The figure 2.3 shows the schematic arrangement of the run-of-river HPP.

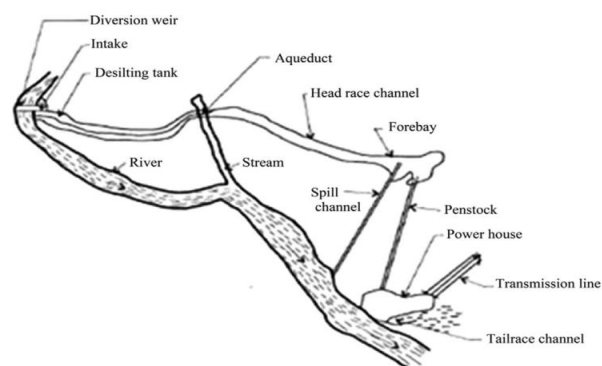


Figure 2. 3 Layout of run of the river HPP[17]

2.6 Solar power plant

The main component of a solar PV plant is a PV cell. PV cells, which are essentially semi-conductors, transform sunlight into usable Direct Current (DC) electrical energy. PV cells are tiny and have a limited energy output of a few Watts (W). PV is one of the most promising ways to continue utilizing energy to support our high quality of living without adding to pollution or global warming[20]. The figure 2.4 is the general layout of grid connected solar PV power plant.

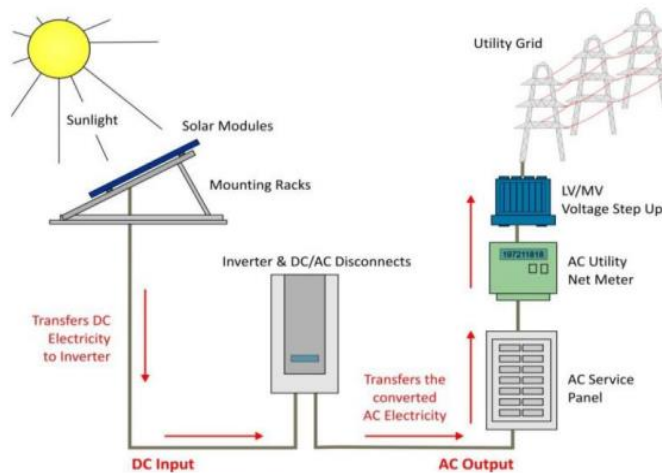


Figure 2. 4 General layout of grid connected solar PV power plant[20].

2.6.1 Main components of solar PV power plant

- ❖ A solar module or panel is made up of solar cells that are connected together and framed. An array is made up of many modules connected in parallel or series. Solar panels are wired in series and connected to a single input to form a string. Multiple strings can be connected in parallel to form a single circuit by using combiner boxes[21].

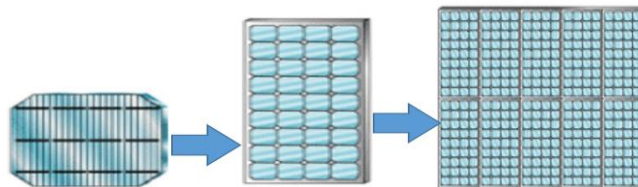


Figure 2. 5 Solar cell ,module and array[21].

- ❖ **Inverter:** Energy from an array or a battery bank is direct current (DC). The inverter changes DC energy to AC energy. Inverters are available in many different sizes for various-sized loads. A string inverter is used to convert DC power from a solar array to AC power and can be connected to an AC distribution power panel(service panel) in a residence or facility or utility grid[21].

2.6.2 Photo voltaic cell characteristics

As it is well known, ideal solar cells behave like a current source connected in parallel with a diode. This ideal model is completed with resistors to represent the losses[22].

The most popular circuit equivalent to a solar cell/panel is shown in figure2.6 below:

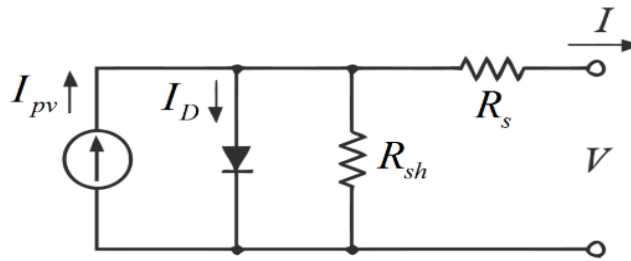


Figure 2. 6 Equivalent circuit of solar cell[22].

The output current of the PV cell is given by equation (2.4)

$$I = I_{pv} - I_0 \left[e^{\frac{q(V+IR_s)}{AkT}} - 1 \right] - \frac{V+IR_s}{R_{sh}} \quad (2.4)$$

Where **I_{pv}** is the photo current; **I₀** is the reverse saturation current of the diode; **q** is the electron charge, **1.602x10⁻¹⁹ c**; **k** is Boltzmann's constant; **1.38x10⁻²³ J/K**; **A** is the diode ideality factor; **R_s** is the series resistance; **R_{sh}** is the shunt resistance; **V** is the output voltage

2.6.3 Photovoltaic cell characteristics with varied insolation

The amount of solar radiation that reaches a certain place over a predetermined period of time is known as insolation, and it varies with latitude and season. Open circuit voltage (V) rises logarithmically and current (I) increases linearly with increasing solar output[23].

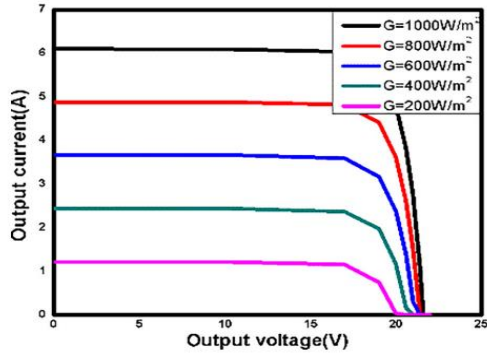


Figure 2. 7 Variation of PV voltage and current with irradiation[23]

2.6.4 MPPT system of solar PV module

From the figure 2.8 below which shows the I-V characteristic and power versus voltage of single solar cell it is clear that the solar PV can generate maximum power only at a single point. The operating voltage or current of a solar cell must match the maximum power point at a specific temperature in order to maximize its power. An electronic circuit used to match the characteristics of module with respect to maximum power to avoid the power loss is known as MPPT tracker[24].

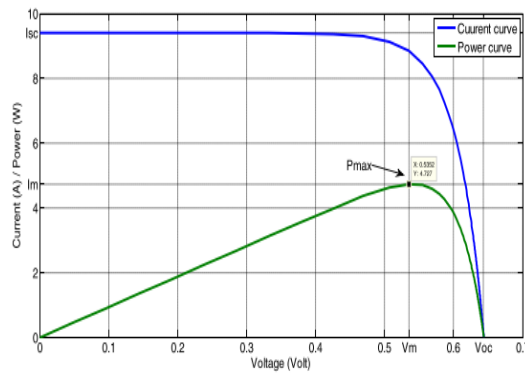


Figure 2. 8 Solar cells I-V and P-V characteristic[24]

2.6.5. Positioning angles of solar PV modules

Tilt angle

The tilt angle of solar PV is defined as the number of degrees that the panels are angled away from the horizontal plane or as the slope angle at which the panels are oriented toward the sun. When it comes to absorbing solar radiation that reaches the panel's surface, the tilt angle of solar panels is important. The tilt angle of photovoltaic (PV) systems with respect to the horizontal plane has a significant impact on their efficiency and performance. The tilt angle can alter how much solar radiation the panel absorbs[25].

Azimuth angle

The angle of the PV modules with respect to the direction of due south is known as the azimuth angle. Where 0° is south, $+90^\circ$ is west, and -90° is east. Variations in the azimuth angle can cause a substantial loss in output power and can also cause a variety of faults in the photovoltaic system[26].

2.7. Optimisation of grid connected solar PV-hydro power plant

2.7.1 Optimisation

- ❖ The process of determining the most advantageous or effective value or situation is known as optimization. Finding the optimal design in relation to a set of restrictions or priorities is the aim of optimization. These include optimizing elements like output, durability, strength, efficiency, and utilization. Optimization, also referred to as mathematical programming, is a set of mathematical ideas and techniques used to solve quantitative issues in a variety of fields, including engineering. It is the process of choosing the best element from a range of feasible options (based on a given criterion). Finding the values of the choice variables that lead to the maximum or minimum of an objective function is the aim of the optimization process. Optimizing hybrid solar PV-hydro power plants entails increasing the system's overall effectiveness, dependability, and financial sustainability[27].

2.7.2 Optimization Methods

Mainly they are three methods of optimization which are classical methods, artificial methods and hybrid methods.

- ❖ The classical approach is defined as the process that employs differential calculation to arrive at the best possible solution. As an illustration, consider mixed integer linear programming (MILP), nonlinear programming (NLP), and linear programming (LP)[28].
- ❖ The majority of artificial methods mimic logical decision-making based on available data. These include machine learning algorithms, genetic algorithms (GA), artificial neural networks (ANN), fuzzy logic (FL), particle swarm optimization (PSO), heuristic optimization, and artificial bee colonies (ABC). Advanced intelligence can be supported by artificial models[29].
- ❖ Hybrid methods: Any method that combines two or more algorithms and allows for the exploitation of these methods' advantages to overcome the limitations of a single algorithm is considered hybrid [29].

CHAPTER THREE: RESEARCH METHODOLOGY

3.1 Research design

The flow chart in the figure 3.1 below shows the description of the research design.

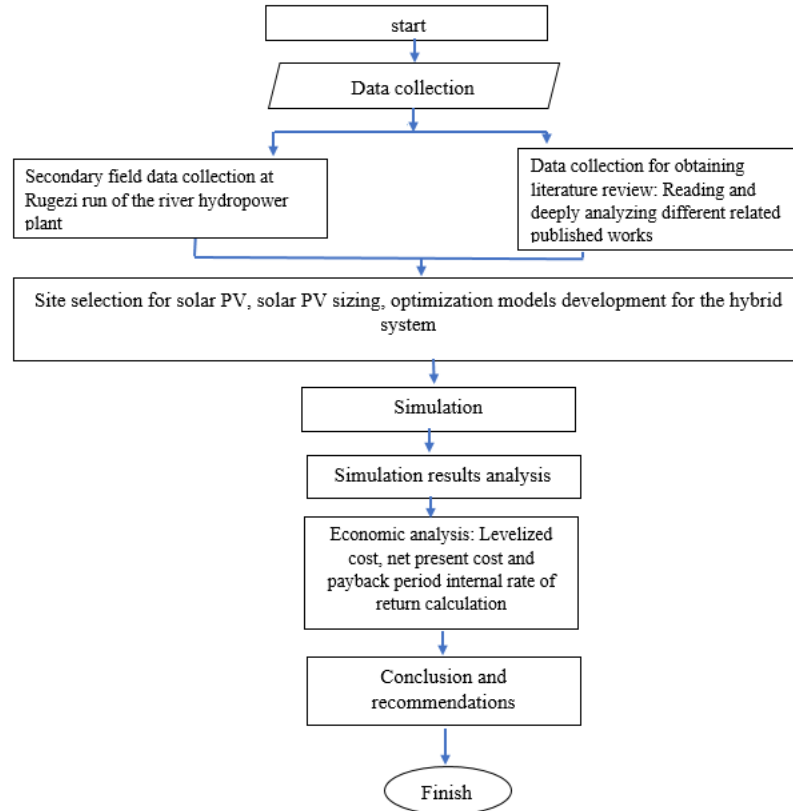


Figure 3.1 Research design flow chart

3.2 Data collection

Field secondary quantitative data were collected from Rugezi run of the river hydropower plant by interviewing Rugezi hydropower plant Engineers, these data are water flow rate during dry seasons, rainy seasons and electrical power produced in those different seasons of the year and

energy purchase agreement between Rwanda Mountain Tea company(RMT) and Rwanda Energy group(REG).

The solar irradiances of selected site of solar PV power plant near Rugezi hydro power plant were imported using meteo norms in PVsyst software by selecting exact location shown on google map.

3.2.1 Description of Rugezi hydro power plant

Rugezi hydropower plant is the run of the river small hydropower plant which was constructed in 2011 In northern province specifically in Burera district, Butaro sector in Mugeru Village near burera lake. The owner of this hydro power plant is Rwanda Mountain Tea ltd[3].

Currently the installed capacity of the plant is 2.672MW. The Rugezi run of the river hydropower plant has two generating units of 1.336MW installed capacity per each generator with line voltage of $V_L=0.660\text{kV}$, the power plant has two power transformers of $0.66\text{kV}/30\text{kV}$ with apparent power of 1600 kVA which are directly connected to the national grid It has also the step down transformer $30\text{kV}/0.4\text{kV}$ which serves the energy to the hydro power plant activities. The Rugezi run of the river hydro power plant has a gross head of 143m with a weir of 1.5m and net head of 135m the length of the channel is 133m and length of Penstock is 338m the two horizontal axis francis turbines of capacity 1378kW per each are used. The power house of the plant is located on -1.4217^0 latitude and 29.8282^0 longitude and altitude of 1912m above the sea level. The figure 3.2 shows the location on map of Rugezi run of the river hydropower.

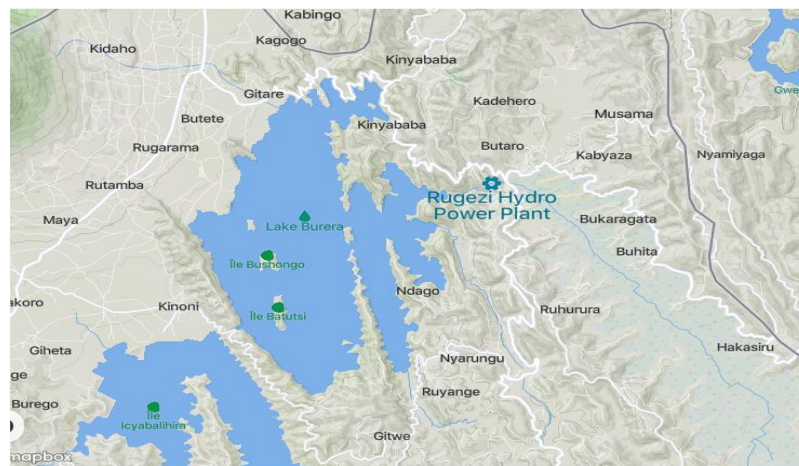


Figure 3. 2 The google map showing the location of Rugezi hydropower plant

3.2.2 Monthly average power produced with corresponding water flow rates

The monthly average power produced with the corresponding water discharge in different seasons of three consecutive years from 2020 up to 2022 were collected at Rugezi run of the river hydro power plant as indicated by the table 3.1, table 3.2 and table 3.3 below:

Table 3. 1 The monthly average power produced with corresponding water flow rates at Rugezi HPP in 2022.

Month	Monthly average water discharge (m ³ /sec)	Monthly average Power produced(MW)	Installed capacity of RUGEZI HPP(MW)	Monthly average Power shortage(MW)
January	0.901	1.061	2.672	1.611
February	1.646	1.938	2.672	0.734
March	1.632	1.923	2.672	0.749
April	1.96	2.312	2.672	0.36
May	2.227	2.617	2.672	0.055
June	1.844	2.167	2.672	0.505
July	0.957	1.139	2.672	1.533
August	1.0629	1.254	2.672	1.418
September	1.718	2.02	2.672	0.652
October	1.317	1.641	2.672	1.031
November	1.264	1.459	2.672	1.213
December	1.046	1.193	2.672	1.479

As indicated by the above table 3.1 it is clear that the highest power shortage in different seasons of the year 2022 occurred in January and it was **1.611MW**

Table 3. 2 The monthly average power produced with corresponding water flow rates at Rugezi HPP in 2021.

Month	Monthly average water discharge(m3/sec)	Monthly average power produced(MW)	Installed capacity of RUGEZI HPP	Monthly average power shortage(MW)
January	1.153	1.311	2.672	1.361
February	1.054	1.209	2.672	1.463
March	0.92	1.0496	2.672	1.6224
April	1.109	1.271	2.672	1.401
May	1.571	1.809	2.672	0.863
June	1.241	1.413	2.672	1.259
July	0.832	0.925	2.672	1.747
August	0.858	0.994	2.672	1.678
September	1.247	1.398	2.672	1.274
October	1.358	1.572	2.672	1.1
November	1.116	1.299	2.672	1.373
December	0.973	1.146	2.672	1.526

From the above table 3.2 it is shown that the highest power shortage in different seasons of the year is **1.747MW** and occurred in July 2021 .

Table 3. 3 The monthly average power produced with corresponding water flow rates at Rugezi HPP in 2020.

Month	Monthly average water discharge(m3/sec)	Monthly average power produced(MW)	Installed capacity of RUGEZI HPP	Monthly average power shortage(MW)
January	1.625	1.867	2.672	0.805
February	1.983	2.105	2.672	0.567
March	1.912	2.191	2.672	0.481
April	1.817	2.037	2.672	0.635
May	1.917	2.175	2.672	0.497
June	1.922	2.107	2.672	0.565
July	1.154	1.32	2.672	1.352
August	0.732	0.822	2.672	1.85
September	0.835	0.948	2.672	1.724
October	1.162	1.329	2.672	1.343
November	1.49	1.72	2.672	0.952
December	1.528	1.758	2.672	0.914

From the table 3.3 above it is clear that the highest power shortage occurred in August 2020 and it was **1.85MW**

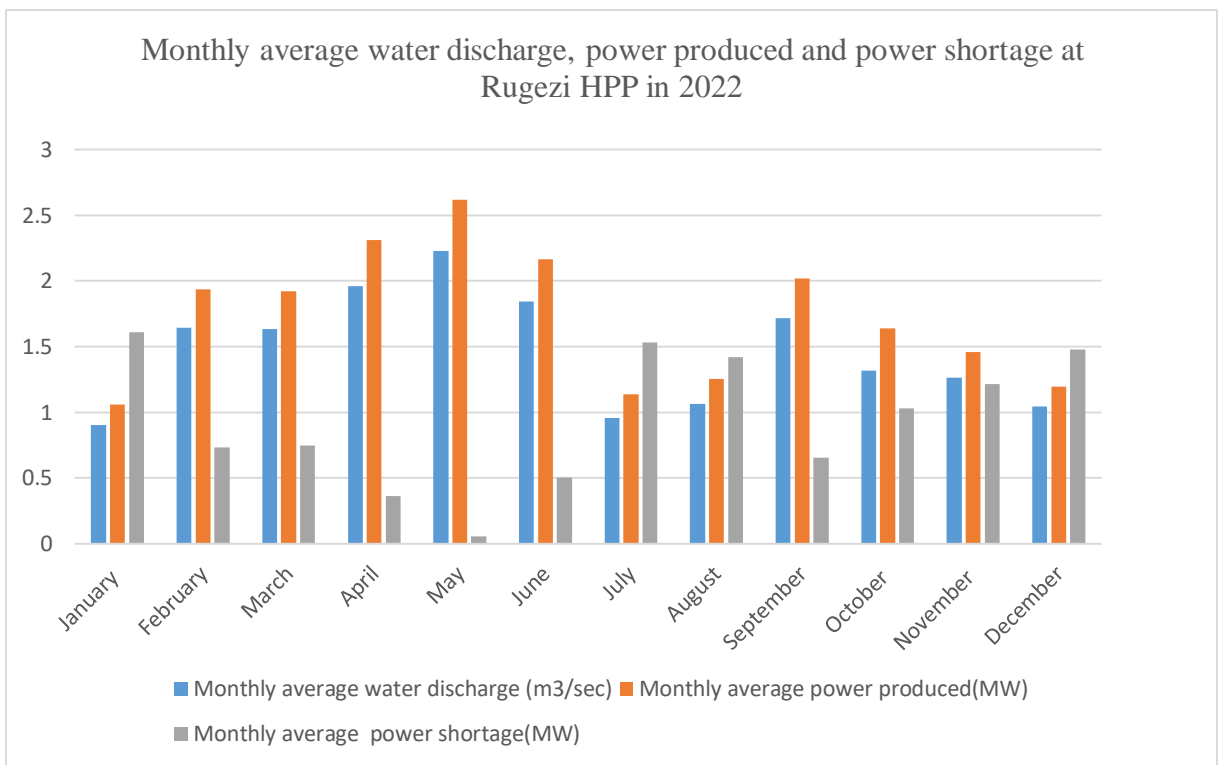
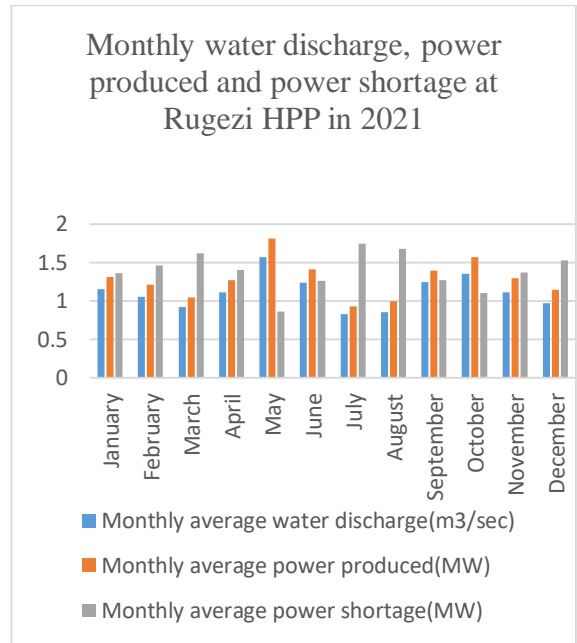
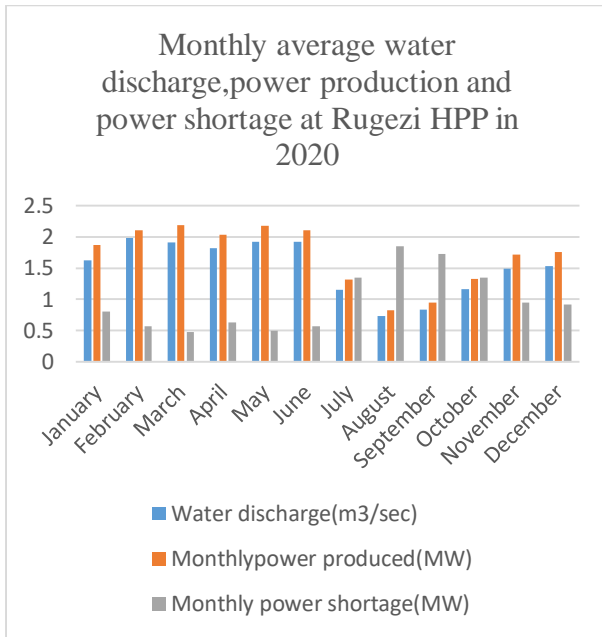


Figure 3. 3 Graph of monthly average power production with corresponding water discharge and power shortage at Rugezi run of the river HPP in 2020,2021,2022

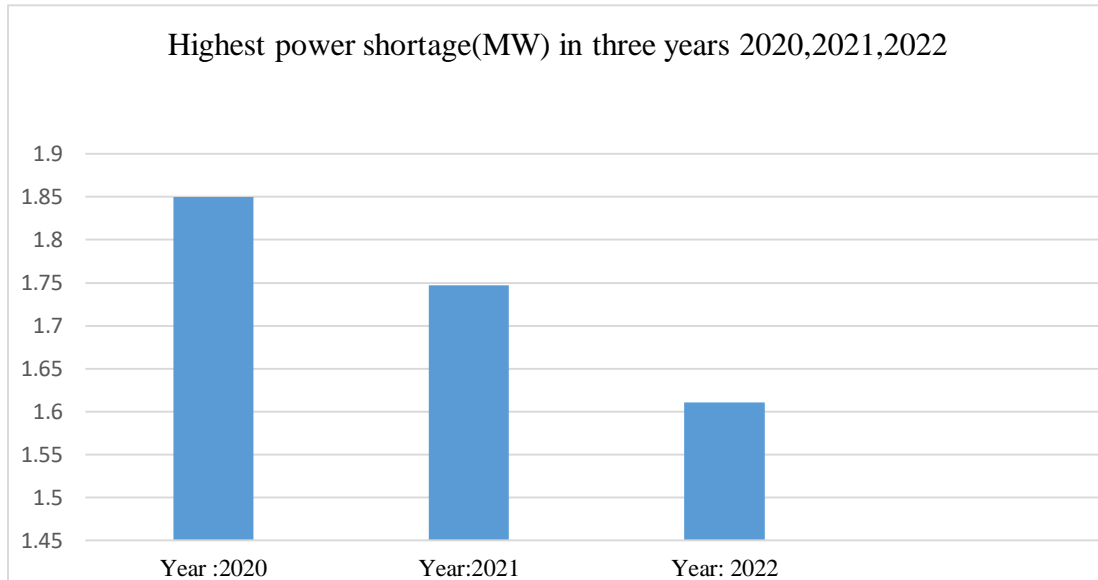


Figure 3. 4 The graphs of highest power shortage in three consecutive years 2020,2021and 2022

From the collected data of the different three consecutive years the highest power shortage is 1.85MW which occurred in August 2020, it is decided that the solar PV power plant to be supporting Rugezi run of the river hydro power plant during dry periods is based on the power shortage of 1.85MW.

3.2.3 Site selection for solar PV power plant

After site survey, the Musebeya site was chosen as the best site for solar power plant according to sun direction and this is near the water intake for hydropower plant. The coordinates, available area and the perimeter the distance from the Musebeya to the hydropower house was calculated using google earth pro and it is found that the Musebeya site is Located on -1.4211° latitude and 29.8327° longitude on altitude of 2043m above the sea level the Musebeya site has surface area of 9771.83m^2 and the perimeter of 774.44m the distance from the site to the hydropower plant power house is 484.32m. The figure3.5 below shows the selected Musebeya site.



Figure 3. 5 Musebeya site for solar PV power plant

3.2.4 The selected Musebeya site monthly solar irradiance profile

Table 3. 4 Solar irradiance profile and temperature at Musebeya(Source PVsyst software, Meteonorm 8.1).

Month	Global solar irradiation (kWh/m ² /month/day)	horizontal irradiation (kWh/m ² /month/day)	Horizontal diffuse solar irradiation (kWh/m ² /month/day)	Temperature/°C
January	5.66		2.45	17.2
February	4.70		2.76	17.2
March	4.47		2.67	17.3
April	4.17		2.58	17.0
May	4.12		2.35	16.3
June	4.87		2.67	16.1
July	5.05		2.39	17.4
August	4.81		2.57	17.1
September	4.76		2.56	17.1
October	3.96		2.55	16.6
November	4.88		2.60	16.4
December	5.09		2.52	16.4

Yearly average	4.71kwh/m²/day	2.55kwh/m²/day	16.8°C/day
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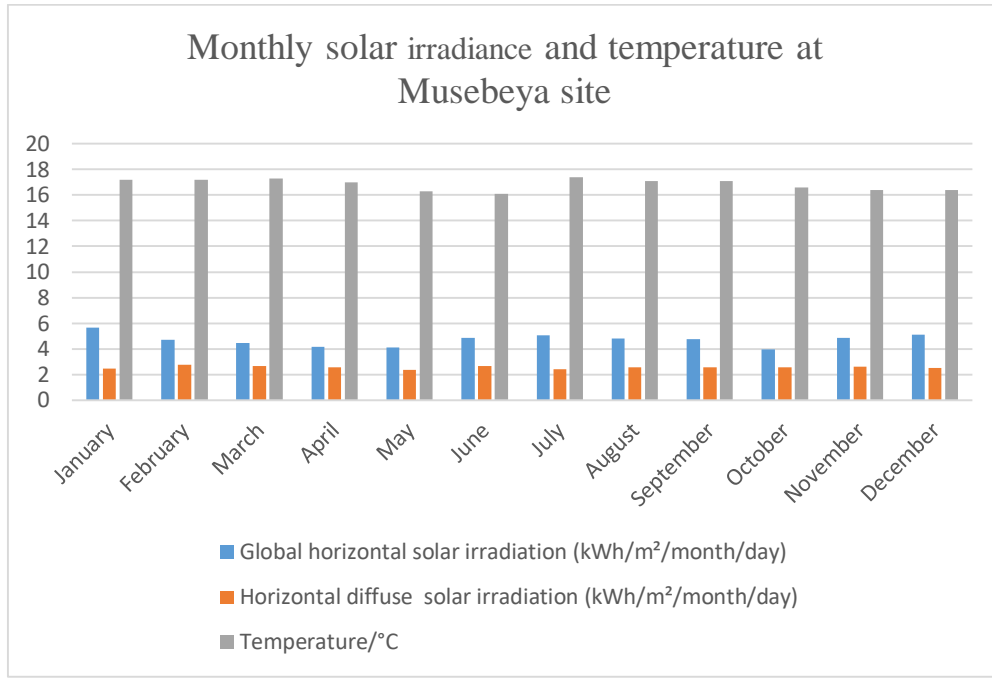


Figure 3. 6 Monthly solar irradiance and temperature at Musebeya site

3.3 Modelling

Different published works related to modelling of hydro-solar PVs hybrid systems are reviewed for the purpose of getting the required information about modelling grid connected hybrid systems of hydro power plants and solar PVs.

Optimization mathematical models of solar PV- Rugezi hydro power plant hybrid system were developed and the data collected from the site are input to the developed optimization models of that hybrid system.

3.4 Simulation

The PVsyst software, Pvsol software, were used to design the required solar PV power plant and ETAP software were used to draw single line diagrams of solar PV power plant and that of the hybrid system combining the solar PV and Rugezi hydro power plant whereas Matlab software is used to simulate linear programming of the designed hybrid power system in order to get the optimum operating point of the system .

3.5. Results analysis

After simulation the results were analyzed to see the optimum operating point of the grid tied hybrid system, the net present cost, the payback period and the minimum cost per unit of energy produced by solar PV power plant is calculated.

CHAPTER FOUR: DESIGN AND SIMULATION

As it is found in chapter 3 the design of this hybrid solar PV /hydro power plant is based on yearly highest power shortage found in August 2020 in three consecutive years 2020-2022 and it was found to be 1.85MWac. The designed solar PV power plant to mitigate this power shortage during dry periods must inject 1.85MWac which is equivalent to 1850kWac.

4.1. SOLAR PV POWER PLANT DESIGN

4.1.1 Solar PV Modules sizing

Different PV module sizes result in varying power output. It is necessary to compute the total peak watt produced in order to determine the PV module's size. The size of the PV module and the site's location climate affect the peak wattage (W_p) generated. We must take into account the "panel generation factor" in this design, which varies depending on the site location.

For this case the total peak wattage produced is equivalent to the total power shortage which is 1.85MWac.

Losses in solar PV module, such as temperature effects, voltage drop, and dirt accumulation, reduces its overall efficiency of the solar panel system. To consider these losses, the total power output is affected by a derating factor. By considering the above effects we decided to design solar PV power plant of 2000kWp.

Because of limited area of Musebeya selected site, taking solar pv module of high peak power reduces the number of solar PV modules required hence the module of $W_p=400W_p$ which is available on the market. The following table 4.1 shows the calculated modules number, modules in parallel, modules in series system voltage and array current. (Refer to appendix B for relations used in this calculation).

Table 4. 1 The required solar PV modules, array current and system voltage at Musebeya site

Module number for solar power plant	5000 modules
Modules in series(Ns)	20modules
Number of modules in parallel(Np)	250modules
current in array	$I_{arr}=250 \times 10.4A=2600A=2.6kA$
System nominal voltage	768V

The table 4.2 below shows the characteristics and technical specification of the selected module

Table 4. 2 Characteristics of the selected module

Manufacturer	AKCOME
Model	SK8610HDGDC-400
Pnom STC power	400Wp
Number of cells	2x60
Module size(WxL)	1.65m ²
Open circuit voltage(VoC)	45.5V
Maximum power point voltage(Vmpp)	38.4V

4.1.2. Inverter sizing

To ensure safe and effective operation, the input rating of the inverter for grid-tied or grid-connected systems must match the rating of the PV array[30]. Now as the total power of array is 2000kWp

Let's take the three phase inverter of power 1000kW, which is available on the market.

The table 4.2 shows the characteristics and technical specification of the selected inverter

$$\text{Number of inverters required} = \frac{\text{The total power required}}{\text{inverter rating}} = \frac{2000kW}{1000} = 2 \quad (4.1)$$

It is clear that two inverters of 1000kW are used.

Table 4. 3 Characteristics of the selected inverter

Manufacturer	Satcon
Model	EQX1000EV400X
Operating mode	MPPT
Minimum MPPT voltage(Vmin)	615V
Maximum MPPT voltage(Vmax)	850V
Grid voltage triphased	400V
Grid frequency	50/60Hz
Maximum efficiency	98.7%

4.1.3 Orientation of solar PV modules for capturing maximum solar radiation

➤ Tilt angle

As the tilt angle, or slope angle, at which solar panels are positioned to face the sun is expressed in terms of degrees from the horizontal plane, when it comes to absorbing solar radiation that reaches the panel's surface, the tilt angle of solar panels is important. The tilt angle of photovoltaic (PV) systems with respect to the horizontal plane has a significant impact on their efficiency and performance. For this design case the tilt angle of 15° was chosen. This chosen angle of 15° is the best suitable on the selected Musebeya site based on the direction of the sun on that site.



Figure 4. 1 Tilt angle at which solar panels are mounted to face the sun on the selected site

➤ **Azimuth**

The angle of the PV modules relative to the direction due south is known as the azimuth angle. Where 0° is south, $+90^\circ$ is west, and -90° is east. Variations in the azimuth angle can impact the PV system through a variety of problems and result in a large loss of output power. In this design the azimuth angle is taken as 0° based on site location and sun direction on that site.

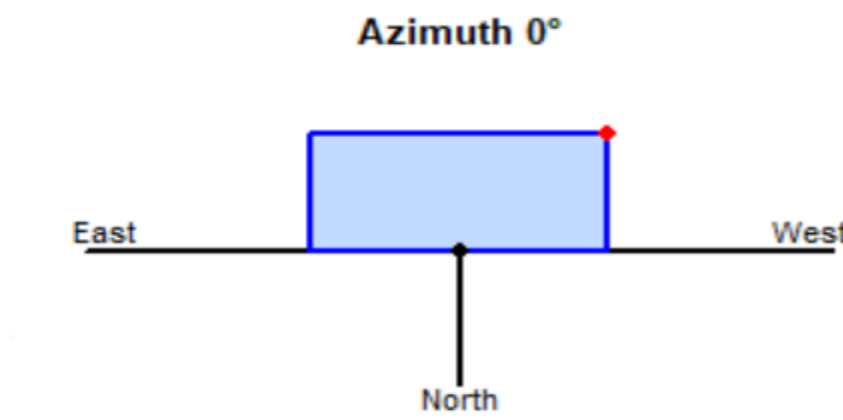


Figure 4. 2 Azimuth angle of solar panel on the selected site

4.1.4 Block diagram of the designed solar PV power plant

The block diagram in figure 4.16 below is the block diagram of the designed solar PV power plant to support Rugezi run of the river hydro power plant, this block diagram shows number of strings with the corresponding inverters of 1000kW and two transformers to step up voltage from 400V to 30kV, the regional national grid voltage.

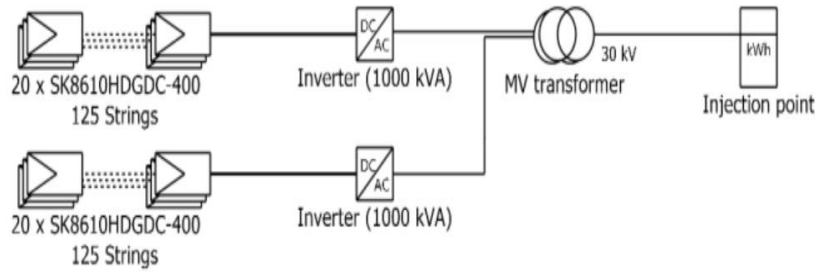


Figure 4. 3 Block diagram of the designed solar PV power plant at Musebeya site in PVsyst7.3 software.

4.1.5 Single line diagram of the designed solar PV power plant

The single line diagram showing the designed solar PV power plant was drawn using ETAP software and it is indicated by the figure 4.4 below.

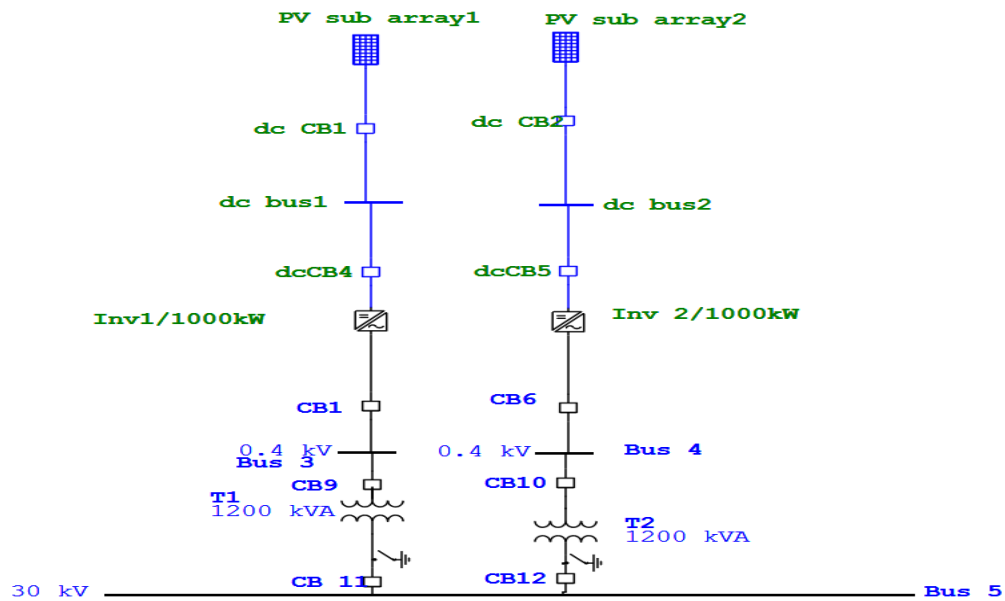


Figure 4. 4 Single line diagram of solar PV power plant in ETAP 14.1.0 software

4.1.5 Wiring layout of the solar PV power plant

The figure 4.5 below shows the wiring layout of the designed solar PV power plant as plant has 20 modules in series and 250 strings, the strings are divided into two parallel groups each group having 125 strings.

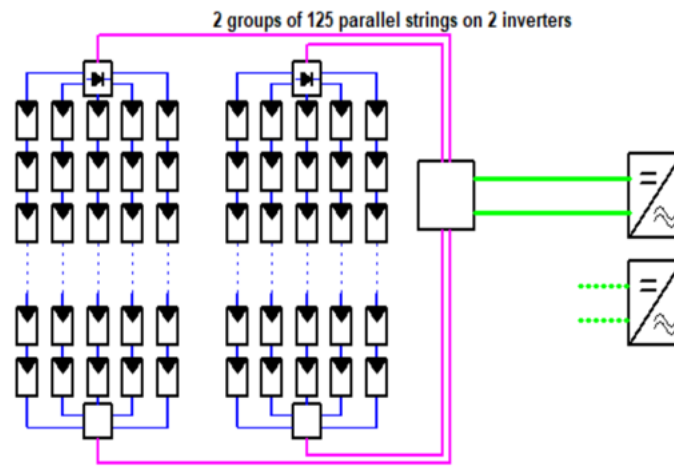


Figure 4. 5 The wiring layout of solar PV power plant

4.1.6 Different views of the designed solar PV power plant in PVsyst software

The different views of figure 4.6 and figure 4.7 and figure 4.8 of the solar PV power plant shown below were designed in PVsyst software, the solar PV array contains twenty five (25) lines where each line contains ten (10) sheds and each shed contains five (5) modules in its length and four (4) modules in its width the total number of modules in one sheds is twenty (20) modules the total number of modules in array is 5000 modules and the area occupied by the solar PV array is 9108m²

➤ **View of the solar PV power plant from sun position**

The figure 4.6. below shows the view of the designed power plant from the sun position

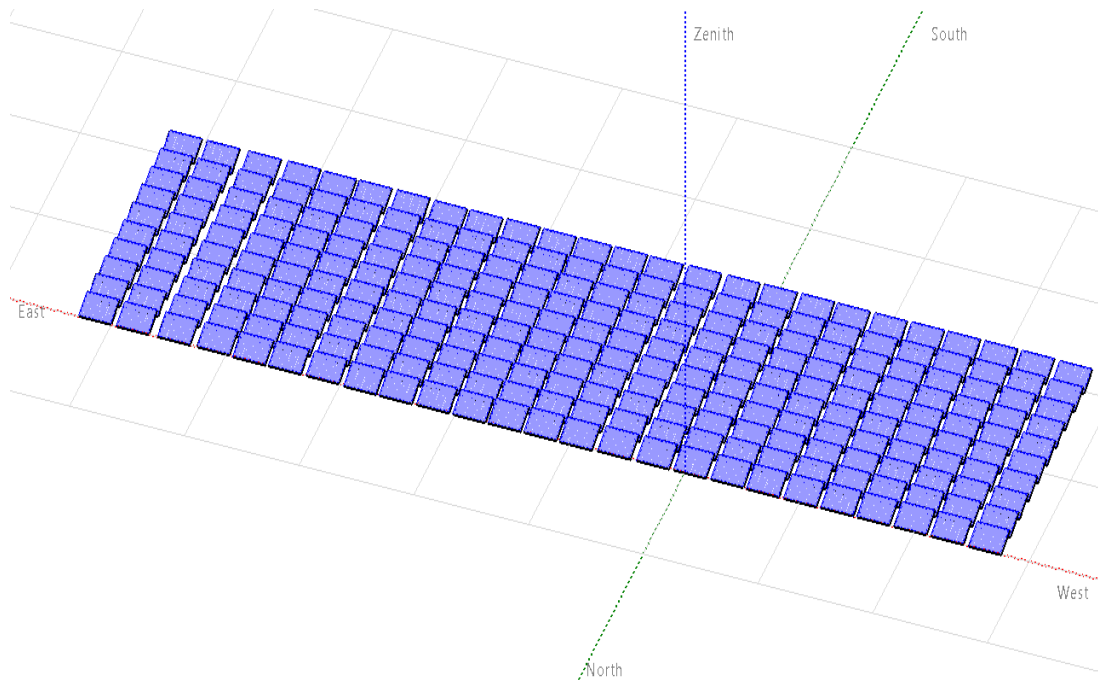


Figure 4. 6 The view of the designed power plant from the sun position

The figure 4.7 below shows the top view of that solar PV power plant

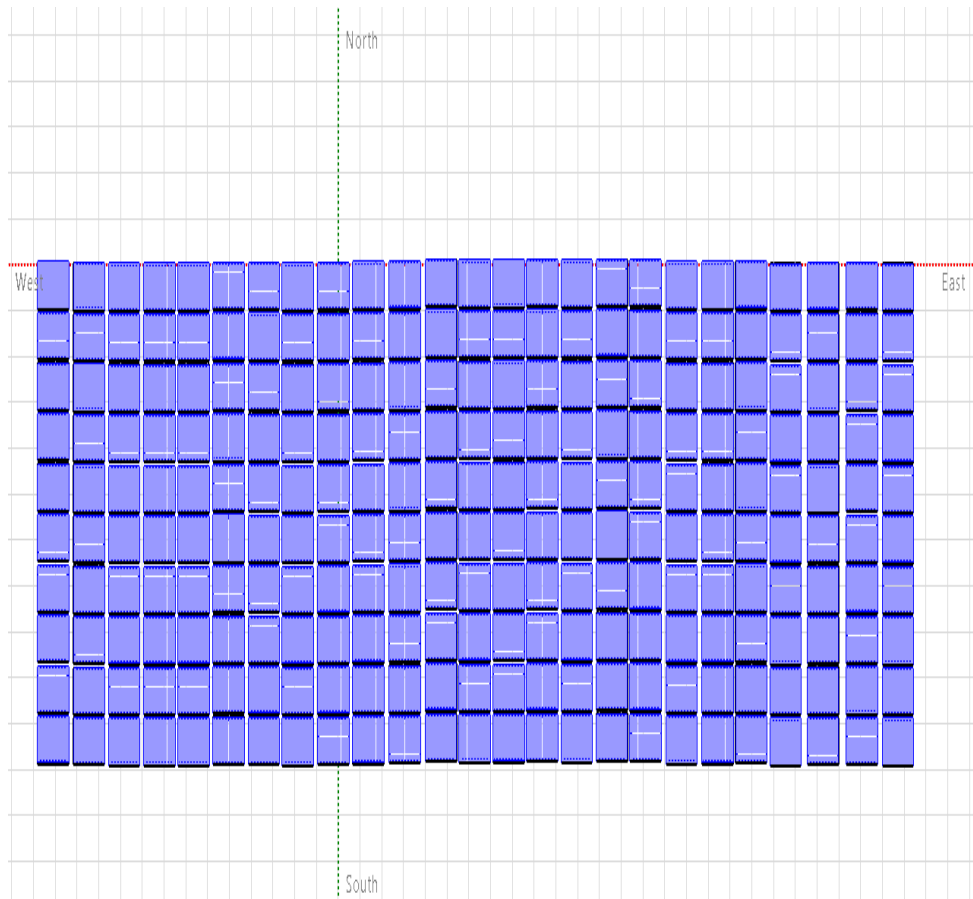


Figure 4. 7 Top view of the designed solar PV power plant

The figure 4.8 below shows the front view and the side view of the designed solar PV power plant



Figure 4.8a)The front view of the designed solar power plant



Figure 4.8b)Side view of the solar power plant

Figure 4. 8 The front and the side views of the designed solar power plant

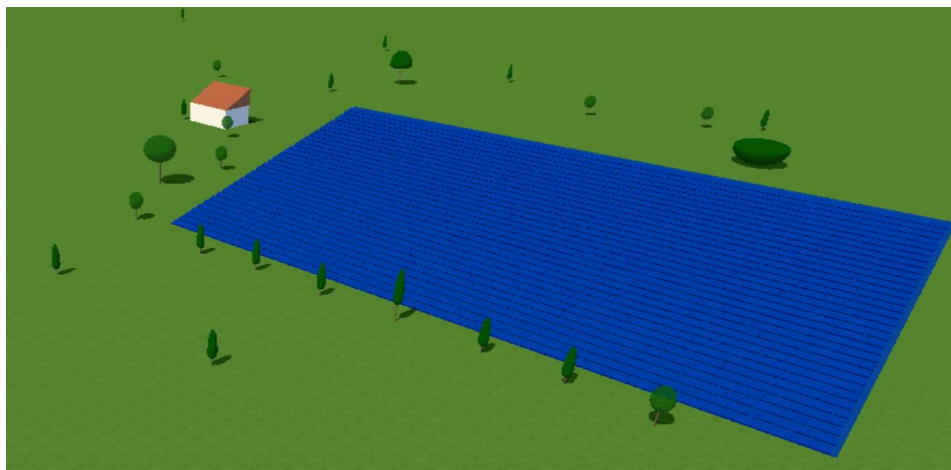


Figure 4. 9 The south east view of designed solar PV power plant in PVsol software

4.1.7 Simulation parameters of the designed solar power plant

The solar PV power plant was designed and simulated using PVsyst 7.3 software and the table 4.3 shows the main simulation parameters of the designed system

Table 4. 4 simulation main parameters of the solar PV power plant

PV module		Inverter	
Manufacturer	AKCOME	Manufacturer	Statcon
Model	SK8610HDGDC-400	Model	EQX1000EV400X
Unit nom. Power	400Wp	Unit nom. Power	1000kWac
Number of PVmodules	5000units	Number of inverters	2units
Nominal (STC)	2000kWp	Total power	2000kWac
Modules	250strings X20 in series	Operating voltage	615V-850V
At operating condition(50 ⁰ c)	P mpp=1884kWp	Max.power(=>25 ⁰ c)	1100kWac
	U mpp=708V	Pnom ratio(DC:AC)	1:00
	Imp=2662A	Total inverter power	
Total PV power	Nominal (STC)=2000kWp	Total power	2000kWac
Total	5000 modules	Number of inverters	2units
Module area	9108m ²	Power nom.ratio	1:00
Array losses			
Thermal loss factor	Module temperature according to irradiance	Uc(const)	20W/Km ²
		Uv(wind)	0.00W/m ² K/m/s
Module quality loss	Loss fraction	-0.3%	
DC wiring losses	Global array resistance	4.3mΩ	
	Loss fraction at	1.5% at STC	
Module mismatch losses	Loss fraction	2.0% at MPP	
Light induced degradation (LID)losses	Loss fraction	1.0%	
Strings mismatch losses	Loss fraction	0.1%	

4.2 Block diagram of a grid connected hybrid system of Rugezi run of the river hydropower plant and solar PV power plant

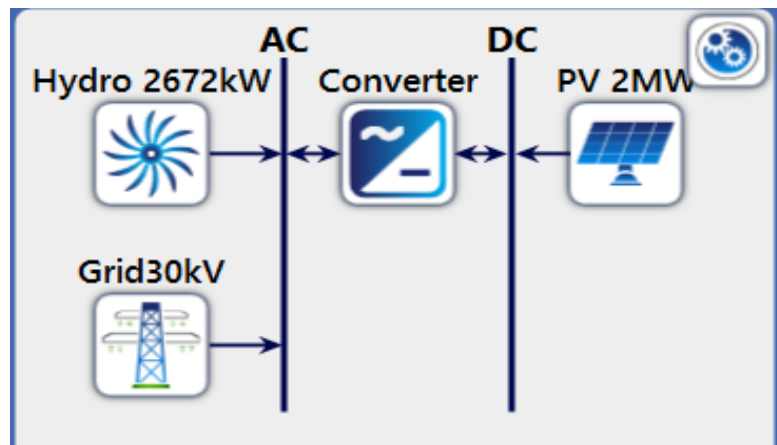


Figure 4. 10 Block diagram of a grid connected hybrid system of Rugezi run of the river HPP and solar PV power plant in Homer software

4.3 Single line diagram of the hybrid system of Rugezi run of the river hydro power plant and solar PV power plant

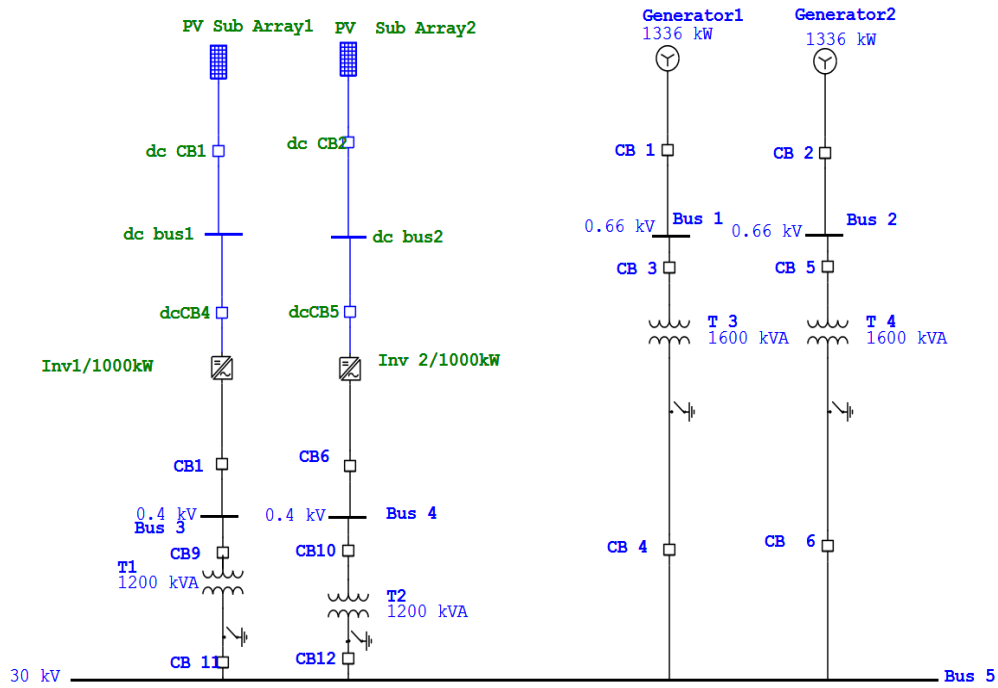


Figure 4. 11 Single line diagram of hybrid system of Rugezi run of the river HPP and solar PV system

4.4 Mathematical modelling and optimization of hybrid system

4.4.1 Optimization mathematical models formulation

The power generated by hydro power is given by:

$$P_{hydro}(t) = \eta_{all} X Q(t) X \delta X g X H_n \quad (4.2)$$

where $P_{hydro}(t)$ is instantaneous power produced at hydropower plant, η_{all} is the overall efficiency of hydropower system $Q(t)$ is water discharge in m^3/sec , δ is water density $1000kg/m^3$, H_n is the available net head in meters and g is the acceleration due to gravity in m/s^2 . Then

$$\begin{cases} P_{hydro}(t) = P_{max} & \text{for } Q(t) = Q_{max} \\ P_{hydro}(t) = \eta_{all} X Q(t) X \delta X g X H_n & \text{for } Q_{min} < Q(t) < Q_{max} \\ P_{hydro}(t) = P_{min} & \text{for } Q(t) = Q_{min} \end{cases} \quad (4.3)$$

$Q(t)=Q_{\max}=2.3\text{m}^3/\text{sec}$ the design flow rate at Rugezi run of the river hydro power plant.

The power produced is $P_{\text{hydro}}(t)=P_{\max}$ (4.4)

From the data collected at Rugezi run of the river hydro power plant, the design flowrate $Q(t)=Q_{\max}=2.3\text{m}^3/\text{sec}$, the net head $H_n=135\text{m}$ the turbine efficiency ($\eta_{\text{turb}}=0.887$) and generator efficiency $\eta_{\text{gen}}=0.97$

The overall efficiency is calculated $\eta_{\text{all}}= \eta_{\text{turb}} \times \eta_{\text{gen}}=0.88 \times 0.97=0.86039=86.039\%$ (4.5)

Then

$$P_{\max} = 0.86039 \times 2.3 \text{m}^3/\text{sec} \times 1000 \text{kg/m}^3 \times 10 \text{m/s} \times 135 \text{m} = 2671542 \text{W} \approx 2.672 \text{MW}$$

(the installed capacity of Rugezi run of the river hydro power)

If $Q(t) < 2.3\text{m}^3/\text{s}$ then the effects of dry seasons on Rugezi hydro power plant start to be considered. The minimum monthly average flow rate $Q(t)_{\min}=0.732\text{m}^3/\text{sec}$ occurred in three consecutive years 2020,2021,2022 was found in August 2020, this water discharge corresponds to the minimum power produced $P_{\min}=0.822\text{MW}$ from the table 3.3 of the data collected at Rugezi run of the river hydro power plant which gives the power shortage of 1.85MW.

The water discharge $Q(t)$ lies between $Q(t)_{\min}$ and $Q(t)_{\max}$ for Rugezi hydro power plant operation

Then $Q(t)_{\min} \leq Q(t) \leq Q(t)_{\max}$ (4.6)

For minimum power production at Rugezi hydro power plant the generating units are capable to generate $P_{\min}=0.822\text{MW}$

Now let X_g be the number of generating units operating in dry periods and W_g minimum capacity of generating unit to be used at Rugezi run of the river hydro power plant

$$W_g * X_g \geq 0.822$$
 (4.7)

And $W_g=P_{\min}=0.822\text{MW}$

As the power required to be injected into the grid is 1.85MW the power shortage in driest season.

The required solar PV power plant must be able to inject 1.85MWac into the grid

Now let Y_{pv} be the number of the required solar PV modules to produce 1850kWp assume the solar system efficiency to be 100% and W_p be the power rating of each PV module in kilowatts

$$\text{Then } W_p * Y_{pv} = 1850$$
 (4.8)

For this case the chosen rating of solar PV is $W_p=400W$ this gives

$$400 * Y_{pv} = 1850 \quad (4.9)$$

The objective function is

$$\text{Minimize } f(X_g, Y_{pv}) = C_1 * W_g * X_g + C_2 * W_p * Y_{pv} \quad (4.10)$$

X_g, Y_{pv} are the design variables

The constraints are given by:

$$\begin{cases} W_p * Y_{pv} + W_g * X_g \leq 2672 \\ W_p * Y_{pv} = 1850 \\ W_g * X_g \geq 822 \\ X_g \geq 1 \\ Y_{pv} \geq 1 \end{cases} \quad (4.11)$$

X_g, Y_{pv} are positive integers

Where C_1 and C_2 are the cost of generating unit and the cost of solar PV module respectively

The average installation cost per kilowatt of solar PV is given by $C_2 = 857\text{USD/kW}$

(source: <https://www.statista.com>)

Installation cost for small scale hydro generator is 11000USD (source: Whole House Generator Cost)

Then the installation cost for the minimum power production at Rugezi $C_1 = 11000\text{USD}/822\text{kW} = 13.38\text{USD/kW}$

Replacing the values of C_1, C_2, W_g and W_p in the objective function and constraints we get

Minimize $f(X_g, Y_{pv}) = 13.38 * 822X_g + 857 * 0.4Y_{pv}$ which is equivalent to

Minimize $f(X_g, Y_{pv}) = 10998.36X_g + 342.8 Y_{pv}$

Subject to the following constraints:

$$\begin{cases} 822 X_g + 0.4Y_{pv} \leq 2672 \\ 0.4Y_{pv} = 1850 \\ 822X_g \geq 822 \\ X_g \geq 1 \\ Y_{pv} \geq 1 \end{cases}$$

X_g, Y_{pv} are positive integers and X_g, Y_{pv} are the design variable

4.4.2 Optimization models simulation

The optimization models associated codes are simulated using matlab software intlinprog solver, the programming is linear programming with integer variables (see appendix A) for programming codes.

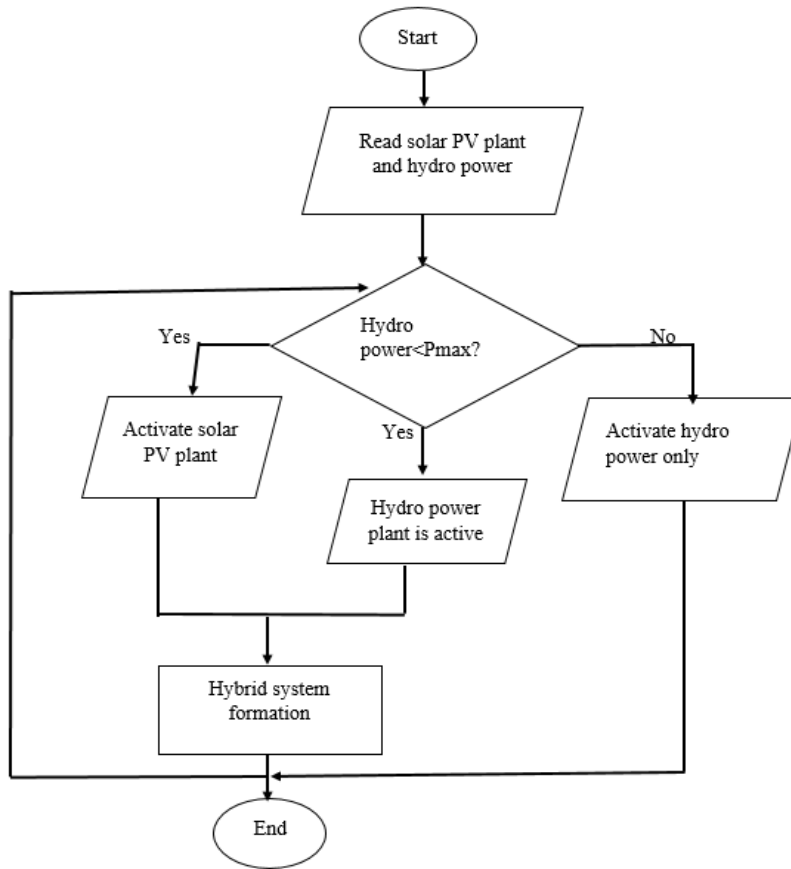


Figure 4. 12 Flowchart showing the operation of rugezi-run of the river hydropower plant and solar PV Power plant hybrid system

CHAPTER FIVE: RESULTS AND DISCUSSION

5.1 Introduction

This chapter shows and describes the results found after simulation of the designed solar PV power plant at Musebeya site in PVsyst 7.3 software and discusses again on the results found after simulation of matlab programming codes based on optimization models of the grid connected hybrid system of Rugezi run of the river hydro power plant and the designed solar PV power plant.

5.2 Simulation results of the designed solar PV power plant at Musebeya site

The figure 5.1 below shows the normalized power productions of the designed solar PV system at Musebeya site over the whole year and it is clear that the greater useful energy is produced in January, July, August, and September the months corresponding to dry seasons in Rwanda. The PV array losses are 0.48kWh/kWp/day, the whole system losses are 0.06kWh/kWp/day and the produced useful energy is 4.09kWh/kWp/day.

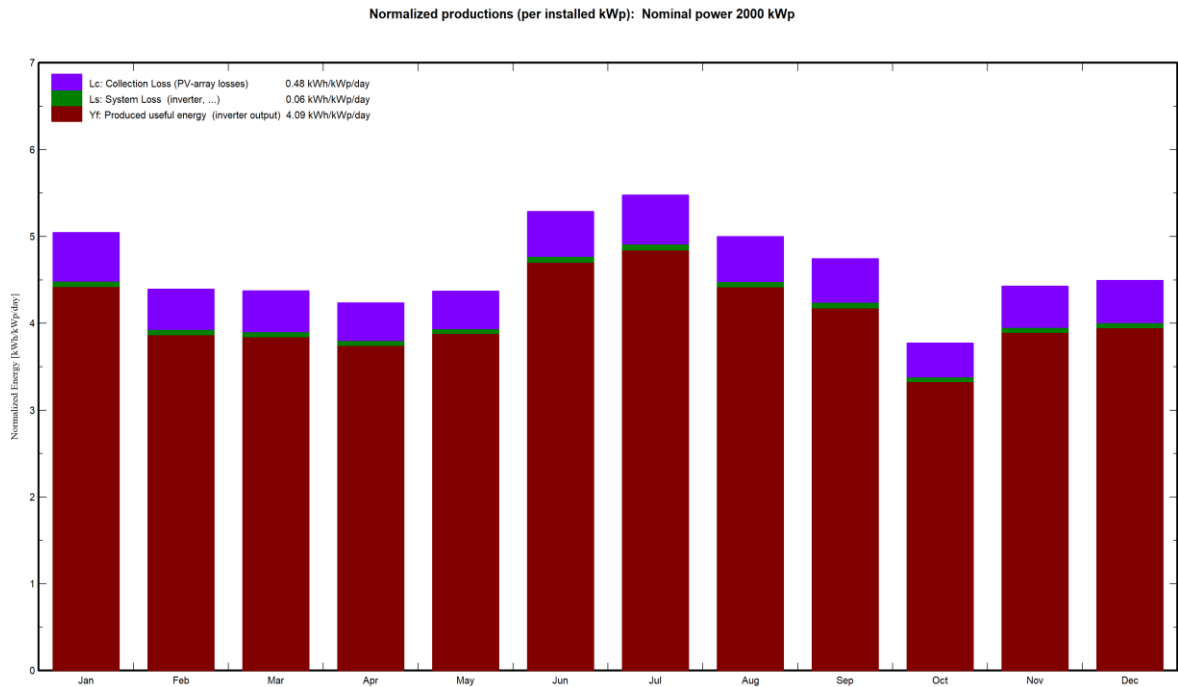


Figure 5. 1 Normalized productions (per installed kWp/day): Nominal power 2000kWp

From the figure 5.2 below it is clear that the performance ratio of the system is $PR=0.882=88.2\%$ which indicates that the system is working well.

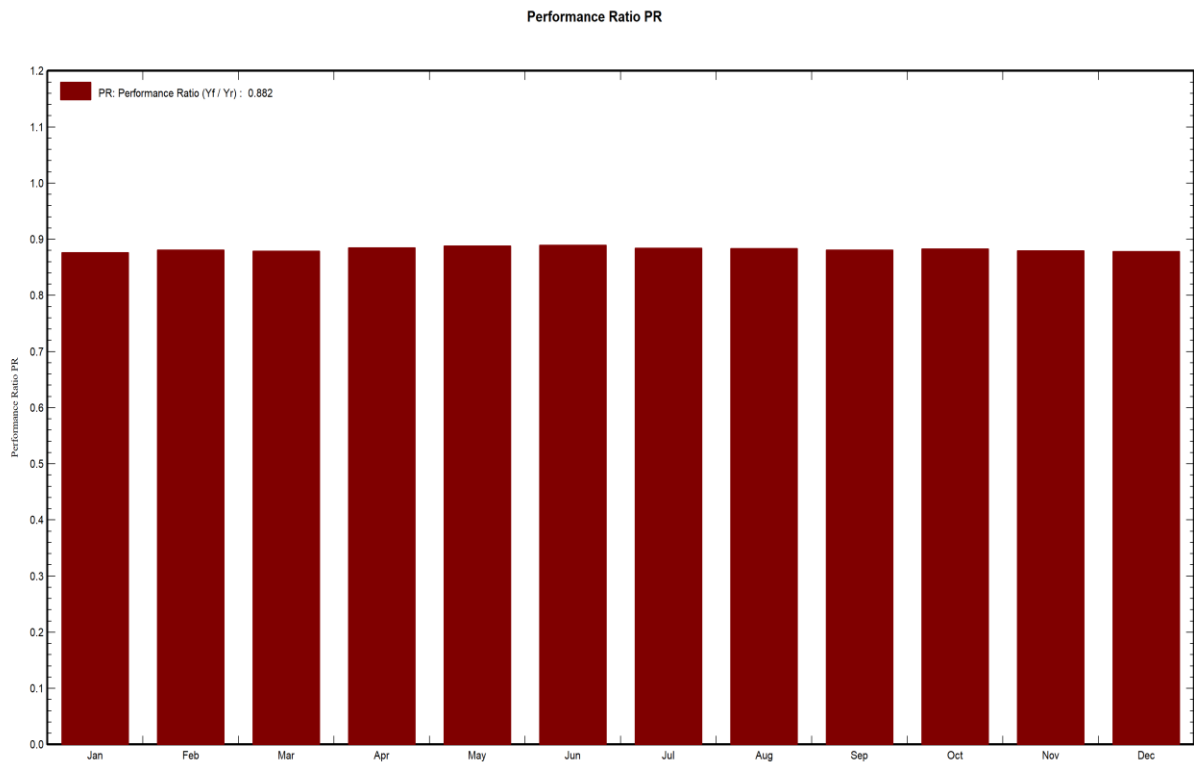


Figure 5. 2 performance ratio of the designed solar PV power plant

Table 5. 1 Balances and main results of the solar PV power plant

**New simulation variant
Balances and main results**

	GlobHor kWh/m ²	DiffHor kWh/m ²	T_Amb °C	GlobInc kWh/m ²	GlobEff kWh/m ²	EArray kWh	E_Grid kWh	PR ratio
January	175.6	75.98	17.16	156.5	151.5	278237	274284	0.877
February	131.5	77.24	17.24	123.1	119.5	220169	216799	0.881
March	138.5	82.88	17.28	135.7	131.9	242174	238538	0.879
April	125.0	77.45	17.00	127.1	123.8	228165	224849	0.885
May	127.8	72.70	16.27	135.6	132.4	244281	240809	0.888
June	146.0	80.02	16.13	158.7	155.2	286434	282453	0.890
July	156.5	73.98	17.41	169.8	166.5	304623	300335	0.884
August	149.1	79.79	17.12	155.1	151.6	277959	274011	0.884
September	142.9	76.76	17.13	142.4	138.8	254593	250811	0.881
October	122.8	78.87	16.56	117.0	113.3	209810	206547	0.883
November	146.5	77.96	16.38	132.9	128.6	237389	233818	0.879
December	157.7	78.08	16.41	139.4	134.4	248551	244907	0.879
Year	1720.1	931.72	16.84	1693.1	1647.7	3032385	2988163	0.882

Where:

DiffHor: Horizontal diffuse irradiation

T Amb: Ambient Temperature

GlobInc: Global incident in collector plane

GlobEFF: Effective global, corr. for IAM and shadings

EArray: Effective energy at the output of the array

E Grid: Energy injected into grid

PR: Performance ratio

GlbHor: Global horizontal irradiation

From the above table 5.1, The monthly average energy produced by the array is greater than monthly average energy injected into the grid this is because of inverter losses, the yearly energy output of the array is 3032385kWh and the energy injected into the grid is 2988163kWh.

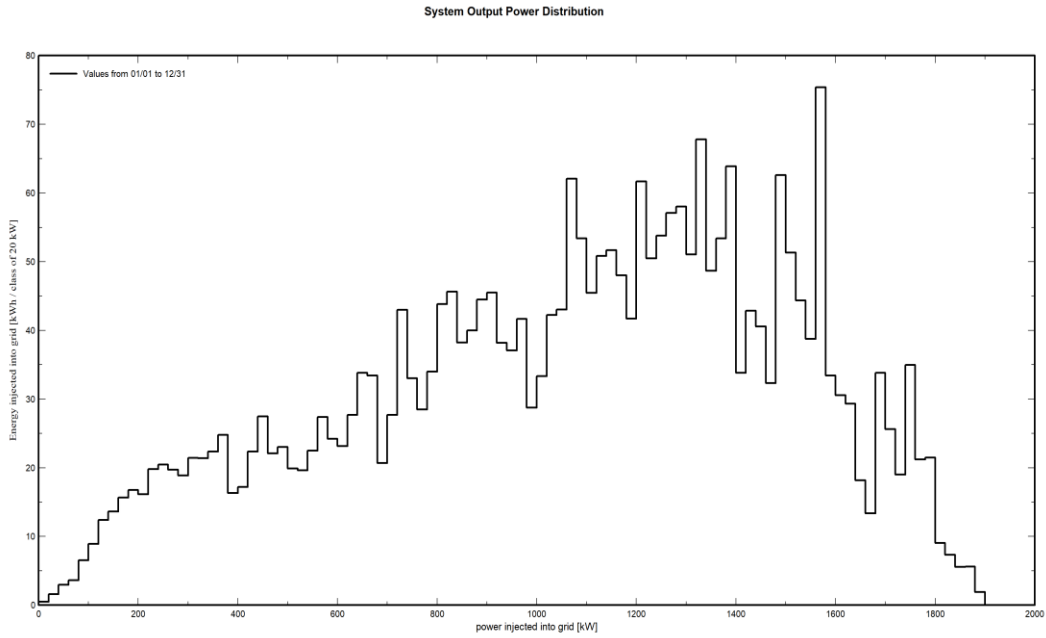


Figure 5. 3 System output power distribution

The figure 5.3 shows the graph of energy injected into grid (kWh/class of 20kW) versus power injected into grid (kW) this power is 1900kW which is little above 1850kW the required output of the system to be injected into the grid for power shortage mitigation and it is clear that the graph is not linear due to the intermittent nature of solar energy.

The figure 5.3 below shows the overall yearly loss diagram of the designed solar PV

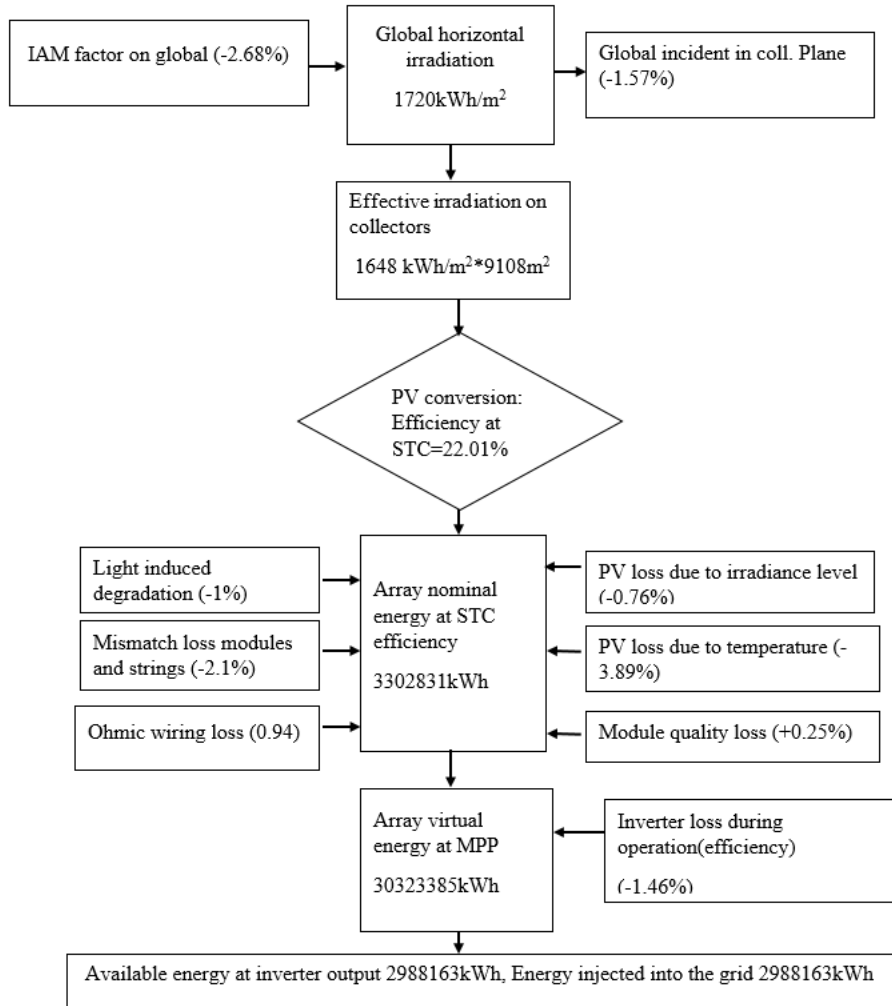


Figure 5. 4 Over all losses diagram of the solar PV power plant

From the above figure 5.4 it is clear that energy balance after removal of all system losses is 2988163kWh which is available at inverter output and injected into the grid.

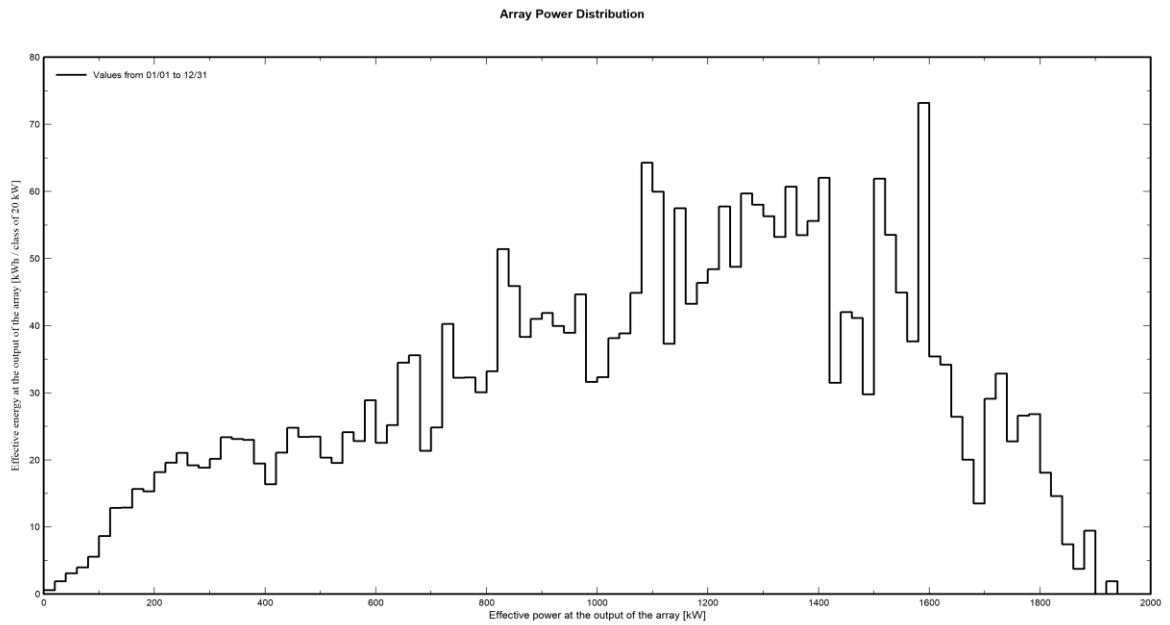


Figure 5. 5 Array power distribution

From the figure 5.5 above, the array output power is above 1900kW but not reaching 2000kW as designed because of array losses and due to intermittent nature of the solar energy and the energy output of the array is not linear.

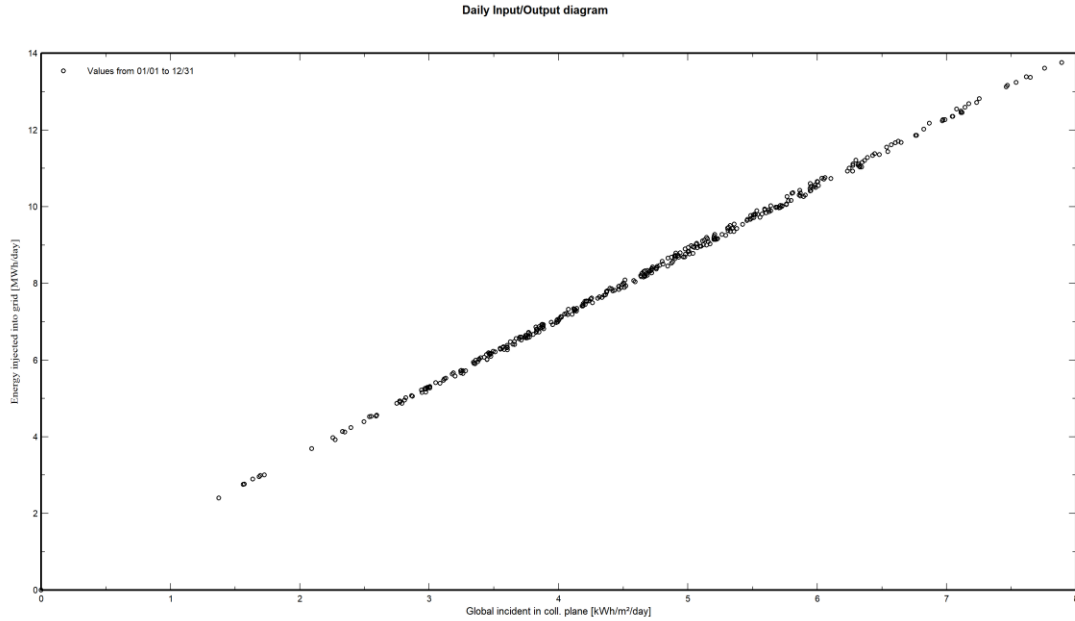


Figure 5. 6 Daily energy output versus global incident

Table 5. 2 Monthly hourly average for energy injected into the grid

New simulation variant
Monthly Hourly averages for E_Grid [kW]

	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	0	186	553	950	1251	1302	1255	1106	911	696	445	193	0	0	0	0	0	0
February	0	0	0	0	0	0	0	160	455	783	1015	1040	993	940	963	727	456	209	3	0	0	0	0	0
March	0	0	0	0	0	0	0	95	424	721	965	1036	1114	940	894	616	522	313	52	0	0	0	0	0
April	0	0	0	0	0	0	0	218	516	716	976	1013	938	945	834	619	506	214	0	0	0	0	0	0
May	0	0	0	0	0	0	0	285	563	845	940	1006	1071	897	898	651	436	176	0	0	0	0	0	0
June	0	0	0	0	0	0	0	299	714	994	1192	1298	1214	1126	991	826	501	260	0	0	0	0	0	0
July	0	0	0	0	0	0	0	265	653	1050	1306	1411	1208	1101	1063	798	572	262	0	0	0	0	0	0
August	0	0	0	0	0	0	0	228	601	976	1057	1219	1177	1108	950	693	571	260	0	0	0	0	0	0
September	0	0	0	0	0	0	9	300	758	1147	1175	1180	1038	773	775	622	417	165	0	0	0	0	0	0
October	0	0	0	0	0	0	32	263	628	871	938	892	659	780	628	552	316	104	0	0	0	0	0	0
November	0	0	0	0	0	0	29	295	637	811	1022	1206	1094	972	673	590	379	86	0	0	0	0	0	0
December	0	0	0	0	0	0	6	220	579	947	1125	1132	954	1003	782	596	425	130	0	0	0	0	0	0
Year	0	0	0	0	0	0	6	235	591	902	1081	1145	1060	975	863	665	462	198	5	0	0	0	0	0

From the above table 5.2 it is clear that the designed solar PV power plant start injecting the energy into the grid at 7 AM except in September, October and November where the energy production starts at 6am and normally energy production ends at 5pm except February and March where there is energy produced at 6pm.

5.3 Economic analysis of the designed solar PV Power plant

5.3.1 Levelized cost, payback period and net present value, internal rate of return calculation for the solar PV power plant

The levelized cost of energy (LCOE), is a measurement used to assess and compare alternative methods of energy production. The LCOE of an energy-generating asset can be thought of as the average total cost of building and operating the asset per unit of total energy generated over an assumed lifetime.

Alternatively, the levelized cost of energy can be defined as the average minimum price at which the electricity generated by the asset is required to be sold in order to offset the total costs of production over its lifetime.

The levelized cost of energy is calculated as shown in equation (5.1)

$$\text{LCOE} = \frac{\text{Present Value of Total Cost Over the Lifetime}}{\text{Present Value of All Electricity Generated Over the Lifetime}} \quad (5.1)$$

Where

The total cost includes initial cost of investment expenditures, maintenance and operations expenditures over a life time and fuel expenditures if applicable. The installation detailed costs of the designed solar power plant are taken after on line market survey by consulting the online markets the providers of solar PV power plant components like Alibaba.com, India MART and made-in-china.com. The table 5.3 below shows installation costs details and table 5.5 shows details on operating and maintenance cost of the solar PV power plant.

Table 5. 3 Installation Costs of the designed solar PV power plant

Items		Quantity	Cost(USD)/unit	Cost(USD)
PV modules SK8610HDGDC-400		5000	104.00	520,000.00
Supports for modules		5000	6.36	31816.20
Inverters EQX1000EV400X		2	27,533.25	55,066.50
Accessories ,Fasteners		1	2447.40	2447.40
Wiring		1	122370	122370
Combiner boxes		5	97.90	489.48
Monitoring system, display screens		1	10,2790.80	10,2790.80
Measuring system, Pyrometer		3	489.48	1,468.44
Surge arrestors		6	1060.95	6,365.69
Fuse links		6	56.49	338.94
Studies and analysis	Engineering	1	6118.50	6118.50
	Permitting and other admin fees	1	1223.7	1223.7
	Environmental studies	1	611.85	611.85
	economic analysis	1	611.85	611.85
Installation	Global Installation cost per module	5000	12.24	61185.00
	Global Installation cost per inverter	2	24.47	48.95
Transport		1	100100.00	100100.00
Settings		1	600,000	600,000
Grid connections		1	15418.62	15418.62
Insurance		1	8,565.9	8,565.9
MV transformers (0.4kV/30kV)		2	14684.4	29368.80
Land costs	Land purchase	1	8586.09	8586.09
	Land preparation	1	122.37	122.37
Energy meters		2	97.90	195.79
Total installation cost				1,675,310.87

Table 5. 4 Depreciable assets

Asset	Depreciation method	Depreciation period	Depreciable(USD)
PV modules SK8610HDGDC-400	Straight line	25years	520,000
Support for modules	Straight line	25 years	31816.2
Inverter EQX1000EV400X	Straight line	25years	55066.5
Total depreciation over the project life time of 25years			606,882.7

Table 5. 5 Operation and maintenance costs of the designed solar PV power plant

Item	Total USD/year	
Maintenance	Provision for inverter replacement	27,533.25
	Solar PV replacement	104.00
	Repairs	2447.40
	Cleaning	2671.10
Salaries	15,000	
Security fund	2216.40	
Taxes	VAT(18%)	25,659.13
	Land taxes	736.67
Total operating and maintenance cost	76,367.96	

From the table 5.3 and the table 5.5 above the levelized cost of energy (LCOE) is calculated.

Taking the installation cost of \$1675310.78 as shown in table 5.3 and operation and maintenance cost of \$ 76,367.96

The estimated life time of the project is taken as 25 years

As the operation and maintenance cost is calculated per year, this cost is calculated over the life time of 25 years of the project.

Operation and maintenance cost=\$ 76367.96X25=\$1,909,199

The yearly energy produced by the solar PV power plant is 2988162kWh

The energy produced over the life time of 25 years is calculated as follows

The energy produced in 25 years=2988162kWhX25=74704050kWh

The total cost of the project over 25years=installation cost+ operation and maintenance cost=
\$1675310.78+\$1,909,199=\$3,584,509.78

$$LCOE = \frac{\$3584509.78}{74704050kWh} = \$0.048/kWh$$

The levelized cost of energy produced by the solar PV power plant is \$0.048/kWh /kWh and this is the typical lowest price at which solar PV power plant electricity can be sold.

Considering feed in tariff between Rwanda Mountain Tea the owner of Rugezi hydro power plant which is 94Rwf/kWh equivalent to \$0.0723/kWh it is shown that the levelized cost of energy is less than feed in tariff at Rugezi HPP. The payback period, Net present value(NPV), Internal rate of return(IRR) and return on investment(ROI) are shown in the simulation results indicated by the table 5.6 below:

Table 5. 6 Financial summary of the solar PV power plant simulated in PVsyst7.3 software

Financing	Own funds	1,675,310.87 USD
Electricity sale	Feed in tariff	0.0723USD/kWh
Duration of tariff warranty	25years	
Payback period	12years	
Net present value(NPV)	1,816,594.79 USD	
Internal rate of return(IOR)	6.69%	
Return on investment	108.4%	

From the table 5.6 above the payback period is 12years, Internal rate of return is 6.69 % and the net present value(NPV) is 1,816,594.79USD

And the project is accepted if net present value is greater than zero

(NPV > 0) then 1,816,594.79USD > 0, hence the project is viable.

Table 5. 7 Detailed financial results of the solar PV power plant

Year	Electricity sale	Own funds	Run. costs	Deprec. allow.	Taxable income	Taxes	After-tax profit	Cumul. profit	% amorti.
0	0	1,675,311	0	0	0	0	0	-1,675,311	0.0%
1	216,044	0	76,368	24,275	115,401	0	139,676	-1,535,635	8.3%
2	216,044	0	76,368	24,275	115,401	0	139,676	-1,395,958	16.7%
3	216,044	0	76,368	24,275	115,401	0	139,676	-1,256,282	25.0%
4	216,044	0	76,368	24,275	115,401	0	139,676	-1,116,606	33.3%
5	216,044	0	76,368	24,275	115,401	0	139,676	-976,930	41.7%
6	216,044	0	76,368	24,275	115,401	0	139,676	-837,254	50.0%
7	216,044	0	76,368	24,275	115,401	0	139,676	-697,577	58.4%
8	216,044	0	76,368	24,275	115,401	0	139,676	-557,901	66.7%
9	216,044	0	76,368	24,275	115,401	0	139,676	-418,225	75.0%
10	216,044	0	76,368	24,275	115,401	0	139,676	-278,549	83.4%
11	216,044	0	76,368	24,275	115,401	0	139,676	-138,872	91.7%
12	216,044	0	76,368	24,275	115,401	0	139,676	804	100.0%
13	216,044	0	76,368	24,275	115,401	0	139,676	140,480	108.4%
14	216,044	0	76,368	24,275	115,401	0	139,676	280,156	116.7%
15	216,044	0	76,368	24,275	115,401	0	139,676	419,833	125.1%
16	216,044	0	76,368	24,275	115,401	0	139,676	559,509	133.4%
17	216,044	0	76,368	24,275	115,401	0	139,676	699,185	141.7%
18	216,044	0	76,368	24,275	115,401	0	139,676	838,861	150.1%
19	216,044	0	76,368	24,275	115,401	0	139,676	978,537	158.4%
20	216,044	0	76,368	24,275	115,401	0	139,676	1,118,214	166.7%
21	216,044	0	76,368	24,275	115,401	0	139,676	1,257,890	175.1%
22	216,044	0	76,368	24,275	115,401	0	139,676	1,397,566	183.4%
23	216,044	0	76,368	24,275	115,401	0	139,676	1,537,242	191.8%
24	216,044	0	76,368	24,275	115,401	0	139,676	1,676,919	200.1%
25	216,044	0	76,368	24,275	115,401	0	139,676	1,816,595	208.4%
Total	5,401,105	1,675,311	1,909,199	606,883	2,885,023	0	3,491,906	1,816,595	208.4%

5.4 Simulation results of optimized hybrid system in matlab software

The programming codes (see appendix A) are simulated in matlab software using intlinprog solver and the following results are generated

x = 1

4625

fval =1.5964e+06

exitflag =1

After simulation of programming codes corresponding to the minimization of the function with its constraints in matlab it has found that, the number of solar pv modules required is 4625 to be connected in series and parallel in order to generate output of 1850Wp to be injected into the grid assumed that efficiency of the system is 100% and one generating unit is in operation and

generating the minimum required power which is 822kW for cost reduction during the driest periods and it is clear that the **objective value** fval is $1.5964e+06 = \$1.5964 \times 10^6$ which is the minimum cost of installation of the grid connected hybrid solar PV power Plant and generators to be used at hydro power plant during the driest period of the year.

CHAPTER SIX: CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

In this research project it was found that highest power shortage which occurred at Rugezi run of the river hydro power plant in three consecutive years 2020,2021,2022 was 1850kW which occurred in August 2020. The solar PV power plant of 2000kWp installed capacity can mitigate the found shortage once combined with Rugezi run of the river hydro power plant to form hybrid system. The yearly average solar irradiance of the selected site was found as 4.71kWh/m²/day which is enough for solar power production considering all system losses, the simulation in PVsyst software has shown that the designed solar PV power plant is capable to inject 1900kWac into the grid which is little above the highest power shortage to be mitigated, the minimum power produced corresponding to the highest shortage was found to be 822kWac. Based on the hybrid system optimization it was found that one generating unit of Rugezi run of the river hydro power plant must be in operation and works in parallel with solar power plant during dry seasons for 1850kWac power shortage mitigation.

6.2 Recommendations

Based on this research project we recommend first of all the Rwanda Mountain Tea Ltd the owner of Rugezi run of the river hydro power plant to implement this project because this will maximize their profit as independent power producers.

We recommend Rwanda energy group to apply the hybrid system technologies by combining solar-hydro power plants because the solar irradiance in Rwanda is generally high for solar PV power plant. The solar PV plants will complement the power produced by hydropower plants during dry periods which highly affected them, as solar energy and hydro energy are renewable energy sources they provide reliable, clean and cost-effective electrical energy. As electrical energy demand increases rapidly all over the world, especially in Rwanda, the hydro-solar PV hybrid systems can produce the reliable energy in all seasons of the year .

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Appendices

Appendix A

Matlab codes for mixed integers linear programming for the hybrid system

```
f=[1099836e-2;3428e-1],
intcon=[1 2],
A=[822 4e-1;-822 0]
b=[2672;-822]
Aeq=[0 4e-1]
beq=[1850]
lb=[1 1],
ub=[inf,inf],
[x,fval,exitflag,output]=intlinprog(f,intcon,A,b,Aeq,beq,lb,ub),
```

Appendix B

Solar PV Calculations relations

Number of required solar modules = $\frac{\text{Total power required}}{\text{Peak power of one module}}$

Number of modules in series (N_s) = $\frac{\text{Nominal system voltage}}{\text{module voltage}}$

Number of modules in parallel (N_p)

Number of modules in parallel = $\frac{\text{Total number of required modules}}{\text{Number of modules in series}}$

Current in the array = *number of modules in parallel X module current*

Appendix C

Data collected at Rugezi run of the river hydropower plant in Rwanda Mountain Tea Company

RWANDA MOUNTAIN TEA
RUGEZI HYDRO POWER PLANT.
ELECTRICITY GENERATION
1.KEY PROJECTS INFORMATION

Project Location	
District, Sector	Burera District, Butaro Sector
River or Lake	Rusumo River
Total Project Land (Acres)	Rfr to REG
Key Project Parameters	
Installed Capacity (MW)	2.6
Project Type (run-of-river or storage)	Run-of-river
Design Flow (m ³ /s)	2.3 m ³ /s
Gross Head (m)	143
Net Head (m)	135
Number of units	2
Type of Generator	MJT 630 M6 B3 Nr.MD16436 I.CI.H
Generator output capacity (MW)	2*1.336
Generator efficiency	0.97
Generator rated voltage (kV)	0.660
Transformer capacity(kVA)	2*1600
Turbine Type (Francis, Kaplan, Crossflow etc.)	Horizontal Francis
Turbine efficiency	0.887
Plant monitoring equipment and tools (software; e.g: SCAD, SIMATIC etc.)	Scada with SIMATIC WIN CC
Length of Channel (m)	133
Length of Penstock (m)	438
Height / Depth of Dam/Weir (m)	1.5

YEAR:2022

Month	Monthly average water discharge(m3/sec)	Power produced(MW)
January	0.901	1.061
February	1.646	1.938
March	1.632	1.923
April	1.96	2.312
May	2.227	2.617
June	1.844	2.167
July	0.957	1.139
August	1.0629	1.254
September	1.718	2.02
October	1.317	1.641
November	1.264	1.459
December	1.046	1.193

**DONE AT RUGEZI,2022
PREPARED BY,**



**NSHIMIYIMANA ERIC
PLANT MANAGER
TEL:0786452774**

YEAR:2021

Month	Monthly average Water discharge(m3/sec)	Monthly average power produced(MW)
January	1.153	1.311
February	1.054	1.209
March	0.92	1.0496
April	1.109	1.271
May	1.571	1.809
June	1.241	1.413
July	0.832	0.925
August	0.858	0.994
September	1.247	1.398
October	1.358	1.572
November	1.116	1.299
December	0.973	1.146

**Done at Rugezi,2021
prepared by,**



**NSHIMIYIMANA Eric
Plant Manager
Tel: 0786452774**

Year: 2020

Month	Monthly average water discharge(m3/sec)	Monthly average Power produced(MW)
January	1.625	1.867
February	1.983	2.105
March	1.912	2.191
April	1.817	2.037
May	1.917	2.175
June	1.922	2.107
July	1.154	1.32
August	0.732	0.822
September	0.835	0.948
October	1.162	1.329
November	1.49	1.72
December	1.528	1.758

**Done at Rugezi,2020
prepared by,**



**NSHIMIYIMANA Eric
Plant Manager
Tel:0786452774**

Appendix E

Monthly meteo data at MUSEBEYA site



PVsyst V7.3.1

Geographical Site		Monthly Meteo Values												
Musebeya Rwanda		Source: PVGIS TMY 5.2												
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Year	
Horizontal global	5.66	4.70	4.47	4.17	4.12	4.87	5.05	4.81	4.76	3.96	4.88	5.09	4.71	kWh/m ² /day
Horizontal diffuse	2.45	2.76	2.67	2.58	2.35	2.67	2.39	2.57	2.56	2.55	2.60	2.52	2.55	kWh/m ² /day
Clearness Index	0.554	0.447	0.424	0.411	0.433	0.532	0.545	0.492	0.463	0.379	0.476	0.505	0.471	ratio
Ambient Temper.	17.2	17.2	17.3	17.0	16.3	16.1	17.4	17.1	17.1	16.6	16.4	16.4	16.8	°C
Wind Velocity	1.3	1.2	1.2	1.2	1.7	1.8	1.5	1.5	1.5	1.3	1.2	1.2	1.4	m/s

Appendix F

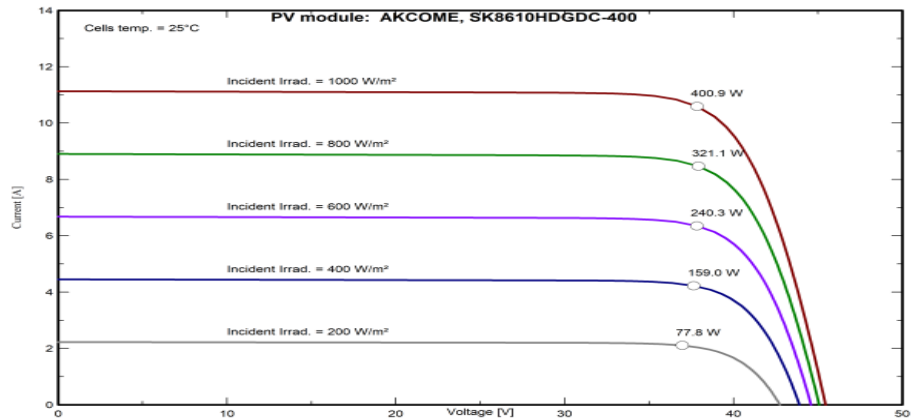
Characteristics of solar PV module selected



PVsyst V7.3.1

PV module - SK8610HDGDC-400

Manufacturer	AKCOME	Commercial data	
Model	SK8610HDGDC-400	Availability :	Prod. Since 2022
		Data source :	Manufacturer 2022
Pnom STC power (manufacturer)	400 Wp	Technology	HIT
Module size (W x L)	1.038 x 1.755 m ²	Rough module area (Amodule)	1.82 m ²
Number of cells	2 x 60	Sensitive area (cells) (Acells)	1.65 m ²
Specifications for the model (manufacturer or measurement data)			
Reference temperature (TRef)	25 °C	Reference irradiance (GRef)	1000 W/m ²
Open circuit voltage (Voc)	45.5 V	Short-circuit current (Isc)	11.13 A
Max. power point voltage (Vmpp)	38.4 V	Max. power point current (Impp)	10.41 A
=> maximum power (Pmpp)	400.1 W	Isc temperature coefficient (mulsc)	5.2 mA/°C
One-diode model parameters			
Shunt resistance (Rshunt)	600 Ω	Diode saturation current (IoRef)	0.017 nA
Series resistance (Rserie)	0.22 Ω	Voc temp. coefficient (MuVoc)	-90 mV/°C
Specified Pmax temper. coeff. (muPMaxR)	-0.24 %/°C	Diode quality factor (Gamma)	1.08
		Diode factor temper. coeff. (muGamma)	0.000 1/°C
Reverse Bias Parameters, for use in behaviour of PV arrays under partial shadings or mismatch			
Reverse characteristics (dark) (BRev)	3.20 mA/V ²	(quadratic factor (per cell))	
Number of by-pass diodes per module	3	Direct voltage of by-pass diodes	-0.7 V
Model results for standard conditions (STC: T=25 °C, G=1000 W/m², AM=1.5)			
Max. power point voltage (Vmpp)	37.8 V	Max. power point current (Impp)	10.64 A
Maximum power (Pmpp)	400.9 Wp	Power temper. coefficient (muPmpp)	-0.24 %/°C
Efficiency/(Module area) (Eff_mod)	22.0 %	Fill factor (FF)	0.793
Efficiency/(Cells area)	24.2 %		



Appendix G

Selected inverter characteristics



PVsyst V7.3.1

Inverter - EQX1000EV400X

Manufacturer: Satcon
Model: EQX1000EV400X

Commercial data

Availability: Prod. Since 2015

Remarks

Technology: Without transformer, IGBT
Protection: NEMA 3R
Control: VFD 4x20 char.

Data source: Manufacturer 2016

Sizes

Width: 4585 mm
Height: 2103 mm
Depth: 785 mm
Weight: 3090.00 kg

Input characteristics (PV array side)

Operating mode: MPPT
Minimum MPP Voltage (Vmin): 615 V
Maximum MPP Voltage (Vmax): 850 V
Absolute max. PV Voltage (Vmax array): 1000 V
Behaviour at Vmin/Vmax: Limitation
Behaviour at Pnom: Limitation

Nominal PV Power (Pnom DC): 1021 kW
Maximum PV Power (Pmax DC): 1134 kW
Power Threshold (Pthresh.): 5000 W

Output characteristics (AC grid side)

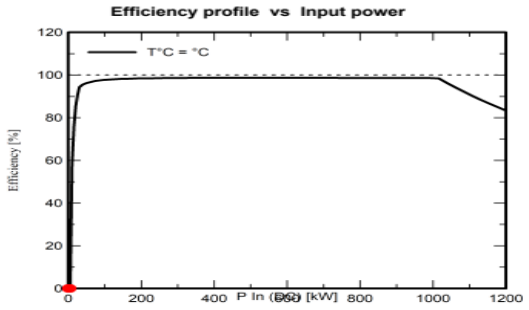
Grid voltage (Imax): Triphased 400 V
Grid frequency: 50/60 Hz

Nominal AC Power (Pnom AC): 1000 kWac
Maximum AC Power (Pmax AC): 1100 kWac
Nominal AC current (Inom AC): 1443 A
Maximum AC current (Imax AC): 1588 A

Maximum efficiency: 98.7 %
European average efficiency: 98.5 %

Remarks and Technical features

Array isolation monitoring
Internal DC switch
Internal AC switch
Output Voltage disconnect adjustment



Appendix H

PV Array Characteristics

PV module		Inverter	
Manufacturer	AKCOME	Manufacturer	Satcon
Model	SK8610HDGDC-400	Model	EQX1000EV400X
(Original PVsyst database)		(Original PVsyst database)	
Unit Nom. Power	400 Wp	Unit Nom. Power	1000 kWac
Number of PV modules	5000 units	Number of inverters	2 units
Nominal (STC)	2000 kWp	Total power	2000 kWac
Modules	250 Strings x 20 In series	Operating voltage	615-850 V
At operating cond. (50°C)		Max. power (=>25°C)	1100 kWac
Pmpp	1884 kWp	Pnom ratio (DC:AC)	1.00
U mpp	708 V		
I mpp	2662 A		
Total PV power		Total inverter power	
Nominal (STC)	2000 kWp	Total power	2000 kWac
Total	5000 modules	Number of inverters	2 units
Module area	9108 m ²	Pnom ratio	1.00

Array losses

Thermal Loss factor		DC wiring losses		LID - Light Induced Degradation				
Module temperature according to irradiance		Global array res.	4.3 mΩ	Loss Fraction	1.0 %			
Uc (const)	20.0 W/m ² K	Loss Fraction	1.5 % at STC					
Uv (wind)	0.0 W/m ² K/m/s							
Module Quality Loss		Module mismatch losses		Strings Mismatch loss				
Loss Fraction	-0.3 %	Loss Fraction	2.0 % at MPP	Loss Fraction	0.1 %			
IAM loss factor								
Incidence effect (IAM): Fresnel, AR coating, n(glass)=1.526, n(AR)=1.290								
0°	30°	50°	60°	70°	75°	80°	85°	90°
1.000	0.999	0.987	0.962	0.892	0.816	0.681	0.440	0.000

Appendix I

Geographical coordinates of the selected site in PVsyst software

Geographical Coordinates Monthly meteo Interactive Map

Location

Site name

Country Region

Geographical Coordinates

Latitude [°] (+ = North, - = South hemisph.)

Longitude [°] (+ = East, - = West of Greenwich)

Altitude M above sea level

Time zone Corresponding to an average difference
Legal Time - Solar Time = 0h 1m