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OPTIMUM DESIGN OF GRID CONNECTED HYBRID SYSTEM OF SOLAR PV AND RUN OF THE RIVER HYDROPOWER PLANT FOR POWER SHORTAGE MITIGATION.

CASE STUDY: RUGEZI RUN OF THE RIVER HYDROPOWER PLANT IN NORTHERN PROVINCE OF RWANDA

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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 was 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 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.

Key words: Renewable energy, Solar energy ,Hybrid system of hydro power plant-solar PV power plant, PVsyst simulation, Matlab optimization

1.Introduction

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 aim of this paper is to

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design the hybrid system combining solar PV and Rugezi run of the river hydro power plant for power shortage mitigation during dry seasons of the year.

2. 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 [4],[5].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 [4].

2.1 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 [6].

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

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

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

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

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

$$P = QX\delta X\ gxHx\eta all \qquad (2.3)$$

Where Q: water discharge in m^3/s, δ: Water density in 1000kg/m3, H: Water head in meter,

g: acceleration due to gravity in m/s^2 and ηall: overall efficiency of hydroelectric power plant[7].

2.1.1Run-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[6].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[8]. The figure 2.1 shows the schematic arrangement of the run-of-river HPP.

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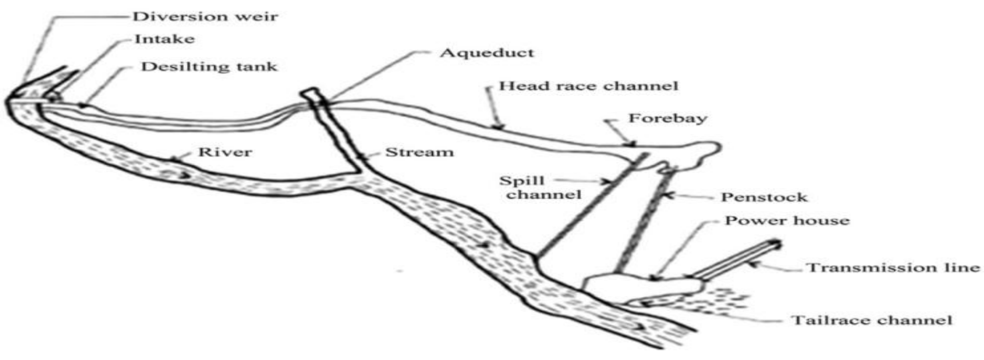

Figure 2. 1 Layout of run of the river HPP[7]

2.2 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[9]. The figure 2.2 is the general layout of grid connected solar PV power plant.

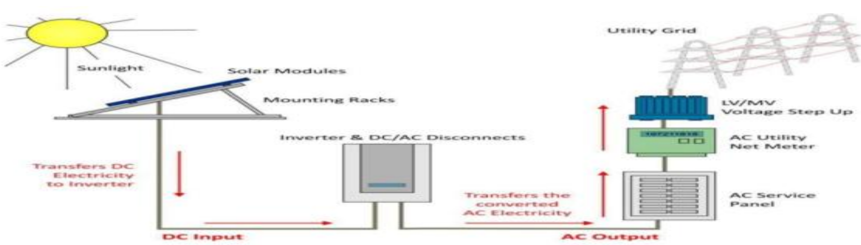

Figure 2. *2* General layout of grid connected solar PV power plant[9].

2.2.1 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[10].

The most popular circuit equivalent to a solar cell/panel is shown in figure2.3 below:

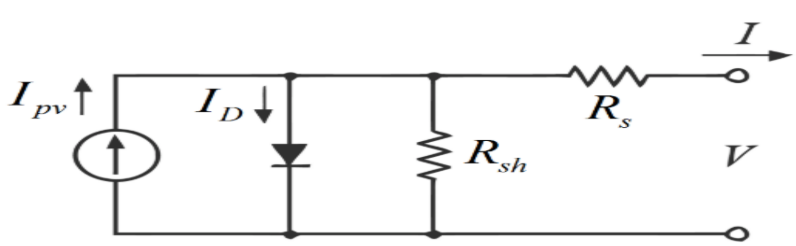

Figure 2. 3 Equivalent circuit of solar cell[10].

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

$$I=Ipv-Io[e^{\frac{q(V+IRs)}{AkT}}-1]-\frac{V+IRs}{Rsh} \qquad (2.4)$$

Where Ipv is the photo current; Io 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; Rs is the series resistance; Rsh is the shunt resistance; V is the output voltage.

2.2.2 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[11]as shown by the figure 2.4below.

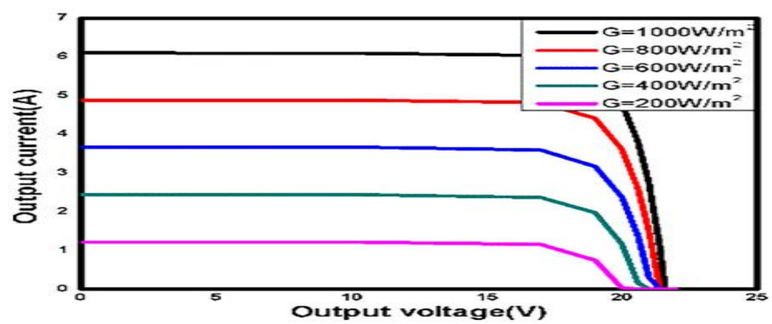

Figure 2. 4 Variation of PV voltage and current with irradiation[11].

3.Methodology

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.

The solar irradiances of selected site of solar PV power plant near Rugezi hydro power plant were imported using meteo norms in PVsyst 7.3 software by selecting exact location shown on google map of that zone. The required solar power plant was designed and simulated using PVsyst 7.3 software. The block diagram of the formed hybrid system was constructed using Homer pro software and the models were optimized in matlab software.

3.1 Monthly average power produced with corresponding water flow rates and solar irradiance profile at the selected solar power plant site

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The figure3.1 below shows Monthly average water discharge,power production and power shortage at Rugezi HPP in 2020

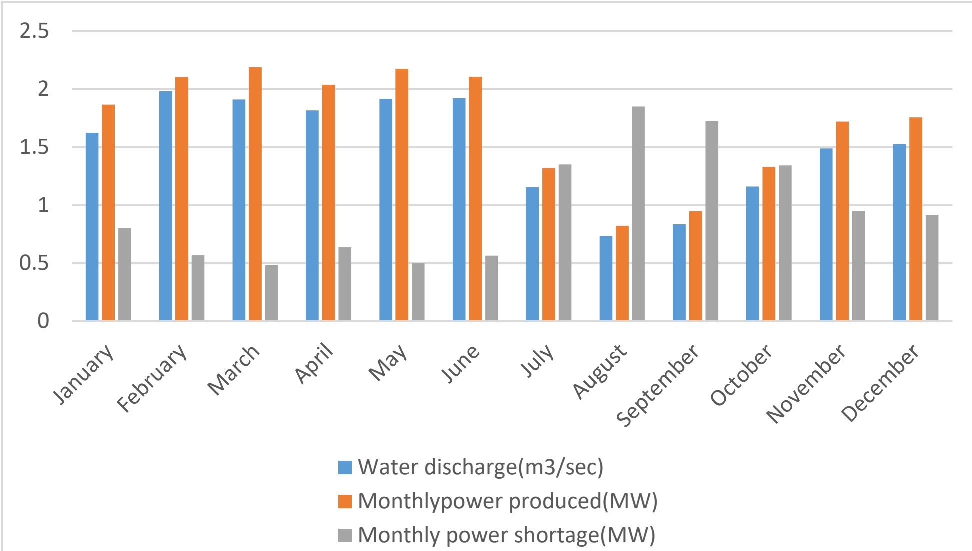

Figure3.1: Monthly average water discharge, power production and power shortage at Rugezi HPP in 2020

The figure 3.2 below shows monthly water discharge, power produced and power shortage at Rugezi HPP in 2021

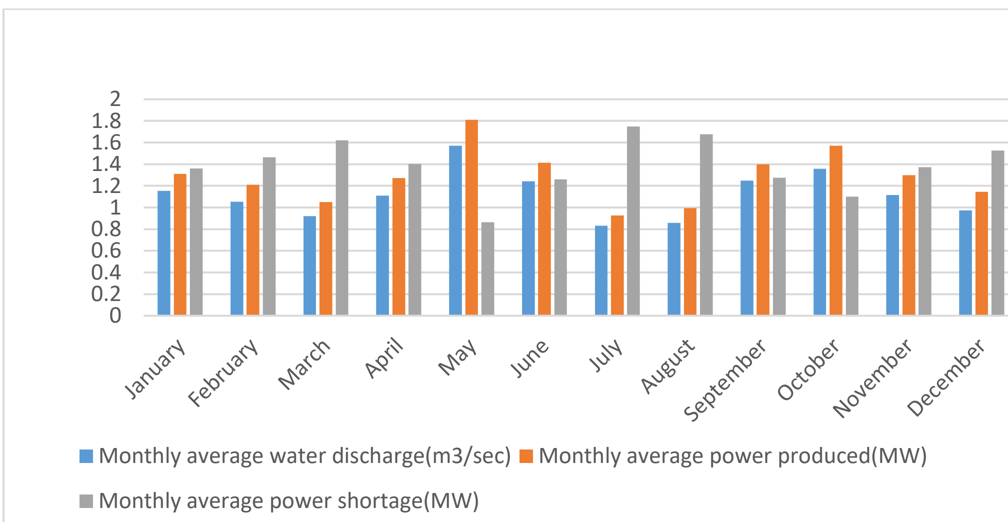

Figure 3.2Monthly water discharge, power produced and power shortage at Rugezi HPP in 2021

Figure 3.3 below shows monthly average water discharge, power produced and power shortage at Rugezi HPP in 2022

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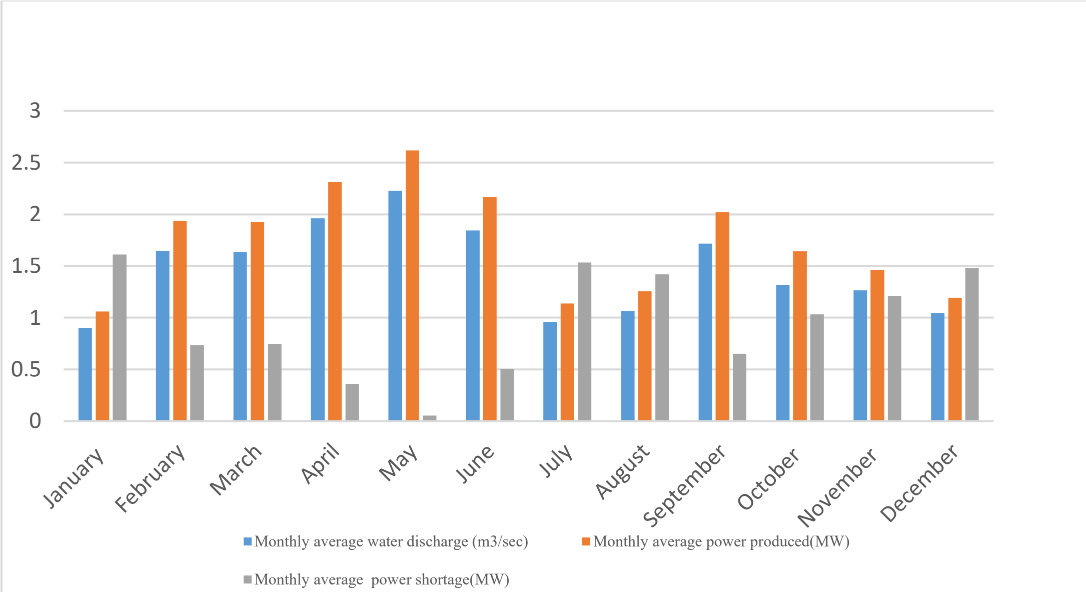

Figure 3.3: Monthly average water discharge, power produced and power shortage at Rugezi HPP in 2022

Figure3.4 below shows monthly solar irradiance at musebeya site

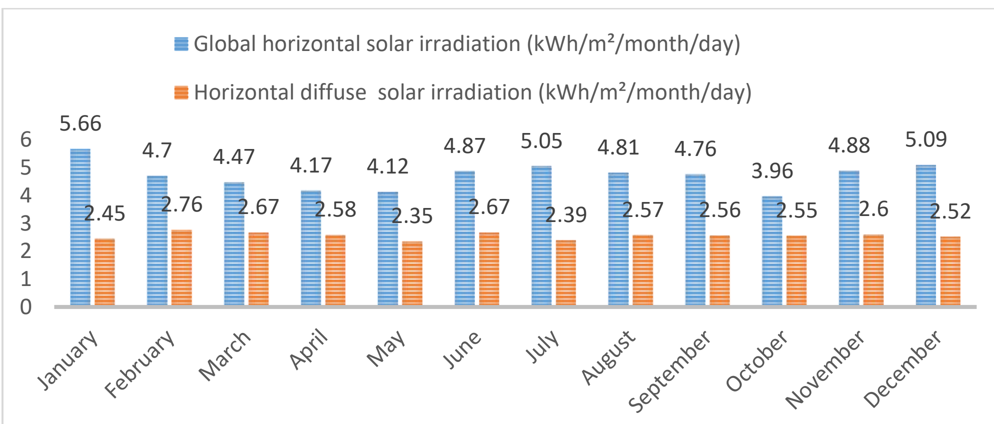

Figure 3.4Monthly solar irradiance at musebeya site

From the collected data of the different three consecutive years the highest power shortage occurred at Rugezi run of the river hydro power plant 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.

3.2Site 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

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area and the perimeter the distance from the Musebeya site to the hydropower house was calculated using google earth pro and it is found that the Musebeya site is Located on -1.4211 ^{0} 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.

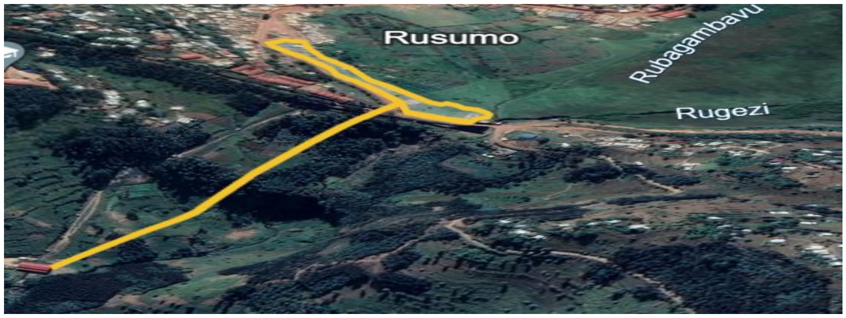

Figure 3. 5 Musebeya site for solar PV power plant

4.RESULTS AND DISCUSSION

4.1Modelling and Optimization

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 the formed hybrid system.

The optimization models associated codes are simulated using matlab software intlinprog solver, the programming is linear programming with integer variables. The power generated by hydro power is given by:

$$P_{hydro}(t) = \eta all\ XQ(t)X\delta X\ gXHn \quad (4.1)$$

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

$$\begin{cases} P\ hydro(t) = Pmax & for\ Q(t) = Qmax \\ P\ hydro(t) = \eta all\ XQ(t)X\delta X\ gXHn & for\ Qmin < Q(t) < Qmax \\ P\ hydro(t) = Pmin & for\ Q(t) = Qmin \end{cases} \quad (4.2)$$

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

$$P_{hydro}(t)=P_{max} \quad (4.3)$$

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

The overall efficiency is calculated $\eta_{all=}\ \eta_{turbX}\ \eta_{gen}=0.88X0.97=0.86039=86.039\%$ (4.4)

Then

$Pmax = 0.86039X2.3m3/secX1000kg/m3x10m/s2x135m = 2671542W = 2.671542MW \approx 2.672MW$ (4.5)

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

If $Q(t)< 2.3m^3/s$ then the effects of dry seasons on Rugezi hydro power plant start to be considered.

The minimum monthly average flow rate $Q(t)_{min}=0.732m^3{}_{/sec}$ occurred in three consecutive years 2020,2021,2022 was found in August 2020, this water discharge corresponds to the minimum power produced P_{min}=0.822MW from figure 3.1 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}=0.822MW

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

$Wg * Xg \ \geq 0.822$ (4.7)

And $Wg=P_{min}$=0.822MW

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 Wp be the power rating of each PV module in kilowatts.

Then $Wp * Ypv = 1850$ (4.8)

For this case, the chosen rating of solar PV is Wp=400W this gives

$400 * Ypv = \ 1850$ (4.9)

The objective function is

Minimize $f(Xg, Ypv) = C1 \ * Wg * Xg \ + \ C2 * Wp * Ypv$ (4.10)

X_g, Ypv are the design variables

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The constraints are given by:

$$\begin{cases} Wp * Ypv + Wg * Xg \leq 2672 \\ Wp * Ypv = 1850 \\ Wg * Xg \geq 822 \\ Xg \geq 1 \\ Ypv \geq 1 \end{cases} \quad (4.11)$$

X_g, Ypv are positive integers

Where C1 and C2 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 =857USD/kW.

Installation cost for small scale hydro generator is 11000USD Then the installation cost for the minimum power production at Rugezi C1=11000USD/822kW =13.38USD/kW

Replacing the values of C1, C2, W_g and Wp in the objective function and constraints we get:

$$\text{Min} f(Xg, Ypv) = 13.38 * 822Xg + 857 * 0.4Ypv \quad (4.12)$$

which is equivalent to

$$\text{Min} f(Xg, Ypv) = 10998.36Xg + 342.8\, Ypv \quad (4.13)$$

Subject:

$$\begin{cases} 822\, Xg + 0.4Ypv \leq 2672 \\ 0.4Ypv = 1850 \\ 822Xg \geq 822 \\ Xg \geq 1 \\ Ypv \geq 1 \end{cases} \quad (4.14)$$

X_g, Ypv are positive integers and X_g, Ypv are the design variable.

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** is 1.5964e+06 =\$1.5964x 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.

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4.2 Block diagram of hybrid system of Rugezi hydropower plant and solar PV power plant

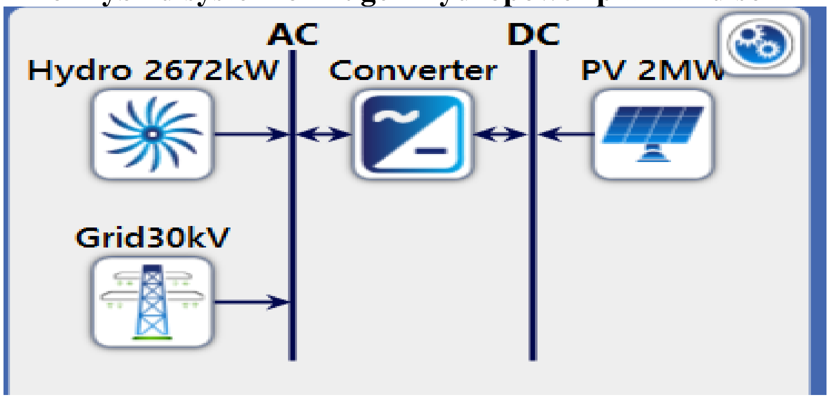

Figure 4.1: Block diagram of the formed hybrid system in homer pro software

4.3 Designed solar PV power plant results at Musebeya site

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 (Wp) 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 the 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 Wp=400Wp which is available on the market. The figure 4.2 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.

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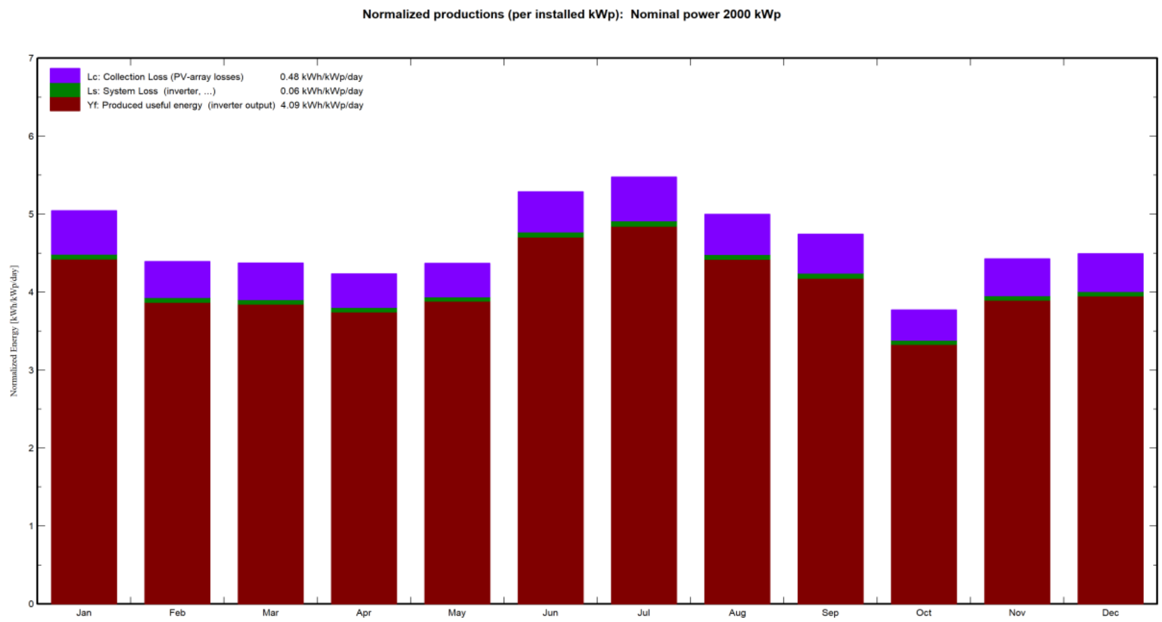

Figure 4.2 Normalized productions (per installed kWp/day): Nominal power.

From the figure 4.3 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.

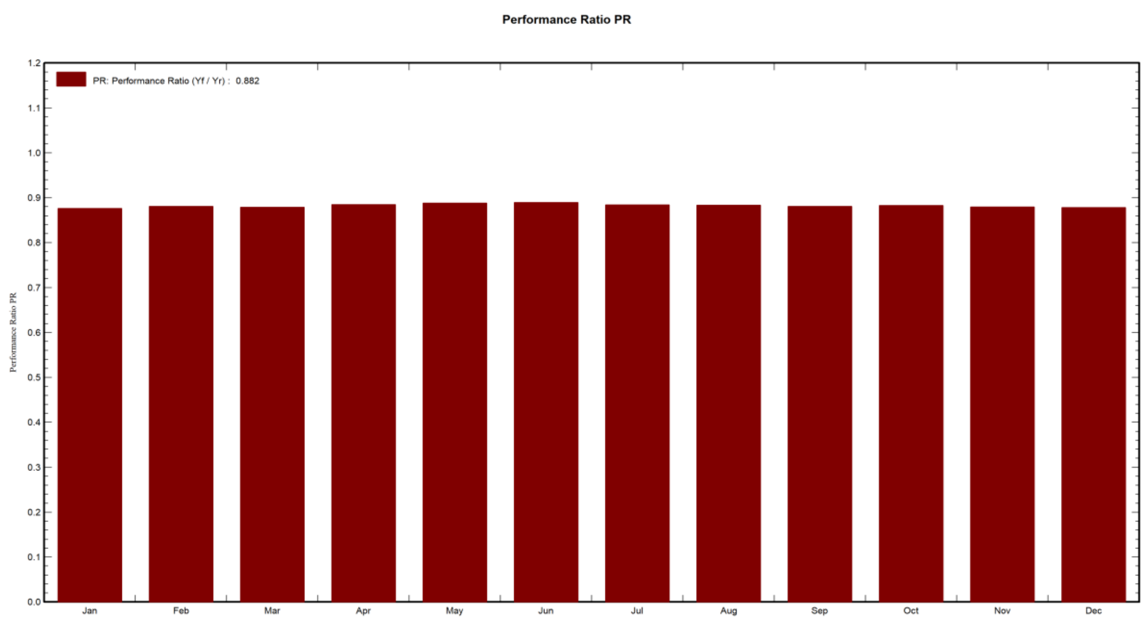

Figure 4.3 Performance ratio of the designed solar PV power plant

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Table 4. 1 Balances and main results of the solar PV power plant

	GlobHor	DiffHor	T_Amb	GlobInc	GlobEff	EArray	E_Grid	PR
	kWh/m²	kWh/m²	°C	kWh/m²	kWh/m²	kWh	kWh	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 :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, EGrid: Energyinjected intogrid, PR: Performance ratio, GlbHor:Global horizontal irradiation. From the above table 4.1, 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.The figure 4.4 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.

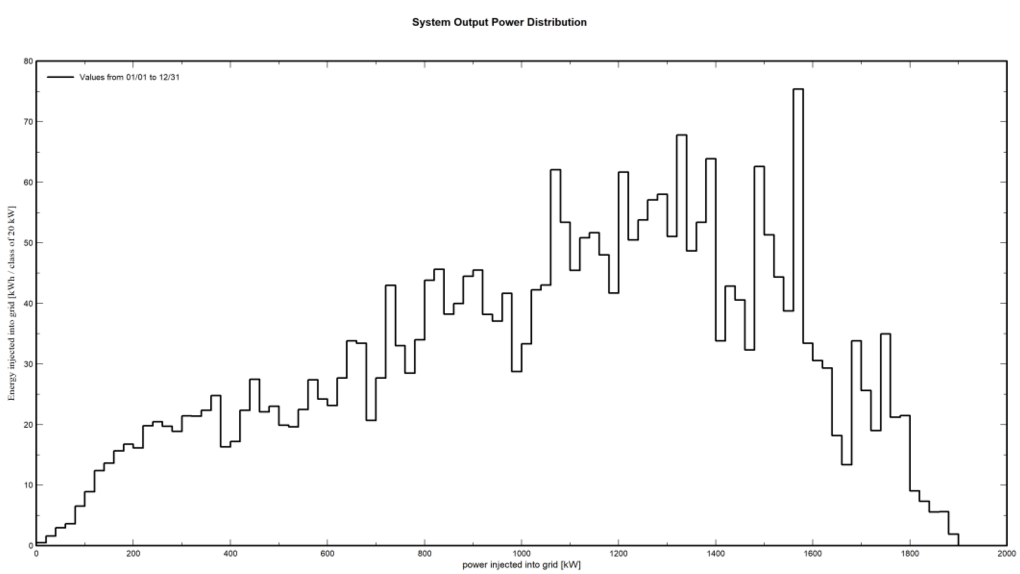

Figure 4. 4 Solar system output power distribution

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Table 4. 2 Monthly hourly average for energy injected into the grid in[kWh]

	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 4.2 it is clear that the designed solar PV power plant start injecting the energy into the grid at 7 AM except in September, October, November and December 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.

4.4 View of solar PV power plant from the sun position

View of figure 4.5 the solar PV power plant below was 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 9108m^2.

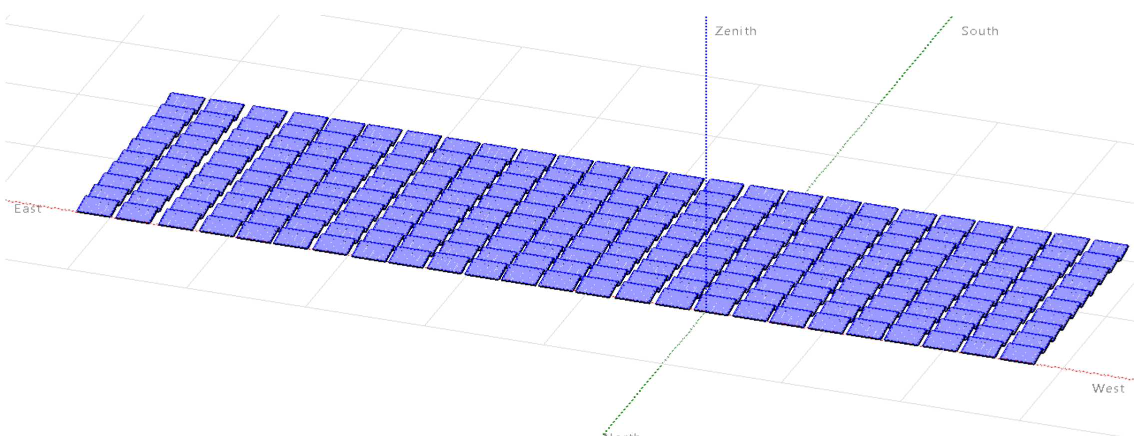

Figure 4. 5 The view of the designed solar pv power plant from the sun position

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5.CONCLUSION

In this research it was found that the 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/m^2/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.

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