Electrical and Thermal performance analysis of a 1000W monocrystalline solar PV Power generator in Eastern Uganda

David Kibirige*, Afam Uzorka*, Ukagwu Kelechi John, Mustafa Mundu Muhamad****

*Department of Physical Sciences, School of Natural and Applied Sciences, Kampala International University Uganda
** Department of Electrical, Telecommunication and Computer Engineering, School of Engineering and Applied Sciences, Kampala International University Uganda

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Abstract- Renewable energy in form of PV solar technology is the fundamental source of electrical power used in present days and nearly eighty percent of the energy is absorbed by the surrounding environment. In other to design a PV system, it is necessary to carry out an electrical and thermal performance analysis of the solar PV power generator to know how efficient the PV cell and the system will be. Electrical and thermal performance analysis of a solar PV power generator includes both energy and exergy analysis. The modeling of both energy and exergy analysis can be done using mathematical concepts. To come up with modeling of energy and exergy both the thermal and electrical quality of the Monocrystalline PV module has been entailed under different seasonal climatic circumstances of eastern Uganda, Busoga region districts. Various parameters such as converted power, exergy, and energy efficiencies have been projected. The simulation results elucidate that the efficiency of the said parameters is altering with respect to the dissimilarity in the solar insolation, temperature, and wind speed. The energy and exergy analysis has been performed by using PV SIM. Time, solar radiation, wind speed, ambient temperature, and cell temperature are used as the input; thermal and electrical efficiencies are the outputs in PV SIM Architecture. It has been evidently observed that the efficiencies are higher in the months of the dry season compared to the month in the rainy season.

Index Terms- Photovoltaic, module energy, exergy, wind speed, PV SIM, solar radiation.

I. Introduction

Fossil fuels will completely be replaced with renewable energy resources in the near future for electrical power generation due to their free pollution techniques and advancement in technology [1, 2, 3]. Solar energy technology using Photovoltaic cells is one of the most common types of renewable sources commonly used [4, 5]. These cells are made from semiconductor materials namely Germanium and Silicon of group 4 in the periodic table [6, 7]. These two elements have photoelectric properties hence capable of converting sunlight energy into electric energy [8, 9, 10]. The performance of these solar panels made depends on a number of factors namely insulation, temperature, direct radiation, solar cell arrangements .design constraints, weather conditions, heat, and area of the PV panel [11, 12, 13]. The exergy and energy analysis are so important that they need further investigations. Both the energy used and the process efficiency are very much required to carry out the energy analysis and balance. It is important to note that the efficiency is calculated from the ratio of solar power output to the actual power supplied to the PV system [14, 15]. During the process of energy analysis validation, there are many deficiencies for instance it is difficult to differentiate power quality and quantity during the performance of the PV cell.

Exergy techniques use the law of conservation of energy and the law of non-conservation of entropy in particular, the conservation energy law is defined by the first law of thermodynamics and non- conservation entropy law is defined by the second law of thermodynamics these help in explaining the details of the losses related to the system.

The analysis of Exergy finds its recarrying application previously due to its many advantages as compared to conventional energy analysis. For this matter, we are capable of getting many outputs and inputs in order to evaluate and complete both Exergy and energy analysis mechanisms. It is worth noting that exergy is easily achieved throughout the process and this helps to put the system in equilibrium when considering its environment just as heat is found in the reservoirs of systems. Exergy is zero when the surroundings

and the system are at equilibrium, when the selection of the sources is appropriate and its magnitude made irreversible then it is possible to improve the efficiency of the system [16, 17, 18].
Several people have conducted research on energy and exergy analysis using experimental data. Badescu et al. [19] made the discussion on chemical and physical properties of a PV energy conversion technique and further provided the details that the open circuit voltage of a solar cell has a dependence on statistical factors and Carnot factors. Lima et al. [20] continued with the investigations about the Carnot factor theorem of solar cells and they were able to establish that multiplication of band gap energy and the Carnot efficiency greatly determine the size of the open circuit voltage. Panwaret al. and Saidur et al. [21, 22] carried out exergy and energy analysis using data from an experiment of 36W PV modules, it is clearly seen that the efficiency of exergy is greatly affected by the temperature of the PV module. The efficiency can be improved if the heat is separated from the photovoltaic panel surfaces. Ghoneim delivered information that the thermal properties, orientation, and optimum values for sizing of the PV modules used for different applications can be redefined hence he developed a computer simulation program for solar water pump systems for Kuwait climatic conditions [23]. Abdallah et al. [24] presented the PV module thermal properties subjected to various conditions of the environment estimating both connective and radiactive heat losses in these panels, making comparisons of the analysis of both measured values under the different speeds of wind and the constant forecasted times. However, Idzkowski came up with a mathematical model in relation to studying the significance of solar insolation, air temperature and wind velocity on the solar cell temperature, and also overlooked free convection and radiation losses from the PV module to the environment [25].
Rukman *et al.* also confirmed the efficiency of exergy and thermal for both PV-T and PV systems, they discovered the exergy efficiency of PVT systems (11.6–16%) as compared to the exergy efficiency of an only PV system (8–14%), this was achieved by using Petela's formula [26]. Dubey et al. have analyzed both the energy and exergy of PV/T air collectors connected in a series arrangement. The cell efficiency and hourly variation of cell temperature have an inverse relationship. Experiments have shown that the solar cell efficiency reduces by 1.6% then the temperature of the solar cell increases by 24.40C [27]. Caglar et al. also experimented with photovoltaic modules for thermal analysis especially exergy efficiency based on the chemical strength of the element. At different operating conditions, they provide a comparative analysis of energy, electrical, and exergy efficiencies [28].
This research work mainly focuses on the thermal performance assessment of the monocrystalline Silicon photovoltaic module on the basis of energetic and exergetic analysis for two seasons (rainy, and dry) of the year, under the climatic conditions of Eastern Uganda The case study is at 1.0^0 latitude and 33.2^0 longitudes, Elevation 1070.0 m time zone GMT +3. The experiments have been conducted for the months of January to October 2022 in actual atmospheric environments from 8.00 AM to 5.00 PM.
A mathematical model has been established to investigate the exergy efficiency using exergy destruction. The experimental factors like wind speed, solar irradiance, short circuit current, open circuit voltage, voltage and current with respect to filling factor, ambient temperature, maximum power point, minimum temperature, maximum temperature, and an average temperature of the photovoltaic module have been considered.

II. Methodology

1. Energy analysis

The energy produced due to the solar radiation (G_s), which is incident upon the solar photovoltaic module having area A_m is estimated according to the formula given below in equation (1).

$$E_{IN} = G_S A_m \quad (1)$$

The power generated from the solar PV panel E_{spv} is expressed in the mathematical model as given below in equation (2).

$$E_{spv} = V_{oc} I_{sc} FF \quad (2)$$

Where V_{oc} is the voltage at open circuit condition, I_{sc} is the current available in a short circuit situation, and FF is the fill factor of the solar PV module. The fill factor of the solar photovoltaic system is normally defined as the ratio of maximum power ($V_{mp} I_{mp}$) to the power obtainable due to the multiplication of both open circuit voltage (V_{oc}) and short circuit current (I_{sc}) and may be expressed as in equation (3).

$$FF = \frac{V_{mp} I_{mp}}{V_{oc} I_{sc}} \quad (3)$$

The energy efficiency is defined in equation (4).

$$ŋ = \frac{V_{oc} I_{sc}}{G_S A_m} \quad (4)$$

2. Exergy Analysis

The exergy efficiency is defined as the output exergy divided by the input exergy as expressed in equation 5.

$$\eta_{EX} = \frac{EX_{OUT}}{EX_{IN}} = 1 - \frac{CV_{IN}}{EX_{IN}} \quad (5)$$

Where EX_{IN}, EX_{OUT} and CV_{IN} are the exergy as input, exergy as output, and irreversibility in the control volume correspondingly. The input exergy includes the intensity exergy of solar radiation. Conferring to R Petela, the input exergy is specified in equation (6).

$$EX_{IN} = EX_{IN}\left[1 - \left(\frac{4}{3}\right)\frac{T_{Amb}}{T_{Solar}} + \left(\frac{1}{3}\right)\left(\frac{T_{Amb}}{T_{Solar}}\right)^4\right] \quad (6)$$

Where T_{Solar} is the temperature of the sun in Kelvin. The irreversibility in the control volume is given in equation (7).

$$CV_{in} = \sum (EX_{Loss} + EX_{Dest}) \quad (7)$$

The losses produced by the heat leakage are specified by equation (8).

$$EX_{Loss} = H_{Loss}A_m\,(T_c - T_{Amb})\left(\frac{T_c - T_{Amb}}{T_c}\right) \quad (8)$$

The entire total heat loss coefficient of the photovoltaic panel consists of the losses due to radiation and convection. The convective heat transfer coefficient as in equation (9).

$$H_{Convection} = 2.8 + 3V_{WIND} \quad (9)$$

Where V_{WIND} is the speed of the wind. The radiative heat transfer coefficient could be expressed as in equation (10)

$$H_{Convection} = \varepsilon_g \delta (T_{SKY} + T_C)\,\{T_{SKY}^2 + T_C^2\} \quad (10)$$

Where ε_g and δ are the emissivity of the PV panel and the Stefan-Boltzmann constant respectively. The effective temperature of the sky (T_{SKY}) is normally lesser than 5-6°C than the ambient temperature. The exergy destruction losses are due to heat caused by temperature deviation of the photovoltaic array and reference environmental state. The exergy destruction is expressed by equations (11) - (14).

$$EX_{DEST\,(opt)} = EX_{IN}\left(\frac{T_{Solar} - T_{Amb}}{T_{Solar}}\right)\{1 - (\tau\alpha)\} \quad (11)$$

$$EX_{DEST\,(\Delta T_{Solar})} = E_{IN}\,(\tau\alpha)\left(\frac{1}{T_C} - \frac{1}{T_{Solar}}\right)T_{Amb} \quad (12)$$

$$EX_{DEST\,(\Delta T_m)} = \frac{m_C\,T_{Amb}C_P}{\Delta t}\left\{In\left(\frac{T_c}{T_{Amb}}\right) - \frac{T_c - T_{Amb}}{T_c}\right\} \quad (13)$$

$$EX_{DEST\,(elect)} = V_{oc}I_{sc} - V_{mp}I_{mp} \quad (14)$$

Where m_C and Δt are the array mass and time interval of the photovoltaic module respectively. The time interval is based on the time step of experimental durations. The specific heat of silicon solar cells (C_P) has been taken in the range of 0.8 to 1.0. The exergy efficiency could be expressed as in equation (15).

$$\eta_{EX} = 1 - \left[\{1 - (\tau\alpha)\} + \frac{EX_{Loss}}{EX_{IN}} + \frac{EX_{DEST\,(\Delta T_{Solar})}}{EX_{IN}} + \frac{EX_{DEST\,(\Delta T_m)}}{EX_{IN}} + \frac{EX_{DEST\,(elect)}}{EX_{IN}}\right] \quad (15)$$

III. Results and Discussions

Weather-related different parameters such as the ambient temperature, wind speed, and solar radiation have been obtained using PV SIM, then the measured parameters such as maximum current, maximum voltage, short circuit current, open circuit voltage, solar cell temperature, fill factor, solar cell temperature of the photovoltaic module has been collected. Similarly, power conversion efficiency with the energy and exergy efficiencies for monocrystalline.

Silicon photovoltaic panels have also been considered. Their performances have been plotted against the experimental time from 8 AM to 5 PM. The variation in different parameters of the polycrystalline solar photovoltaic modules against time intervals for January and February has been displayed in figures 1 and 2.

Table 1: Monthly average daily solar energy and weather data for Eastern Uganda

Month	Number of the days	Representative days of the month	Av. wind speed (m/s)	Av. instant Solar radiation (W/m^2)	Sunshine duration (hours)	Average ambient temp. (ºC)
January	31	5,16,25	4.75	490.33	3.46	5.00
February	28	5.17,26	4.79	500.12	4.43	5.10
March	31	4,15,28	4.32	671.05	5.32	7.80
April	30	2,15,21	4.00	650.18	6.85	13.00
May	31	3,15,23	3.80	601.95	8.61	15.70
June	30	1,11,27	3.19	870.14	10.51	20.40
July	31	6,17,31	3.78	920.70	11.17	22.80
August	31	3,16,29	4.70	900.83	10.14	22.80
September	30	7,15,22	4.80	662.55	7.83	21.10
October	31	4,15,30	4.30	800.00	5.22	16.70

Table 2: Electrical and thermal performance of the proposed system

Month	**Top PV temp. (ºC)**	**Bottom PV temperature after cooling (ºC)**	**Total Instant Pout (W)**	**Daily Thermal Energy (kWh/d)**	**Daily Electrical Energy (kWh/d)**
1	37.6	28.0	1000.1	3.5	13.9
2	37.8	29.0	900.2	4.5	17.9
3	49.2	37.9	995.7	7.1	33.2
4	51.1	39.6	1000.3	8.9	45.9
5	51.5	40.9	900.8	10.6	59.0
6	49.2	39.8	1000.2	11.5	68.2
7	47.8	38.3	800..0	11.5	69.2
8	47.4	38.9	1010.4	10.3	62.0
9	47.7	39.0	1004.1	8.6	47.8
10	49.6	38.9	1110.2	6.3	33.6

Table 3: Thermal, Electrical, and overall efficiency of the system

Month	**Thermal Energy Efficiency (%), □pv**	**Electrical Energy Efficiency (%),□th**	**Overall system efficiency (%),□s**
1	20.9	47.9	68.8
2	20.6	46.6	67.2
3	20.6	53.9	74.5
4	19.5	58.9	78.4
5	19.9	63.3	83.2
6	19.7	67.8	87.5
7	20.9	65.7	86.6
8	19.8	70.8	90.6
9	20.6	64.1	84.7
10	20.5	61.4	81.9

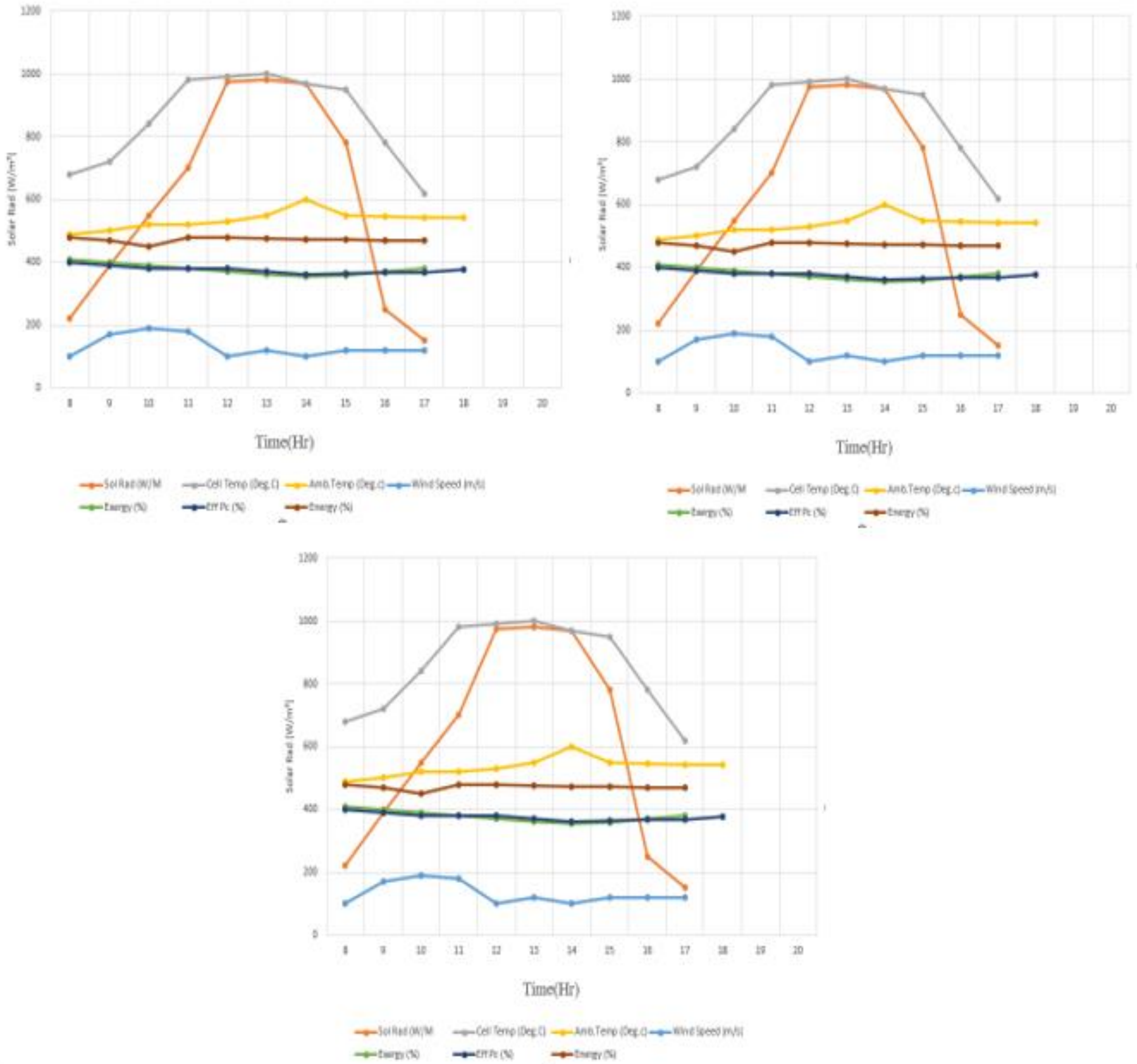

Figure 1: Time-dependent variations of the parameters for three days of January

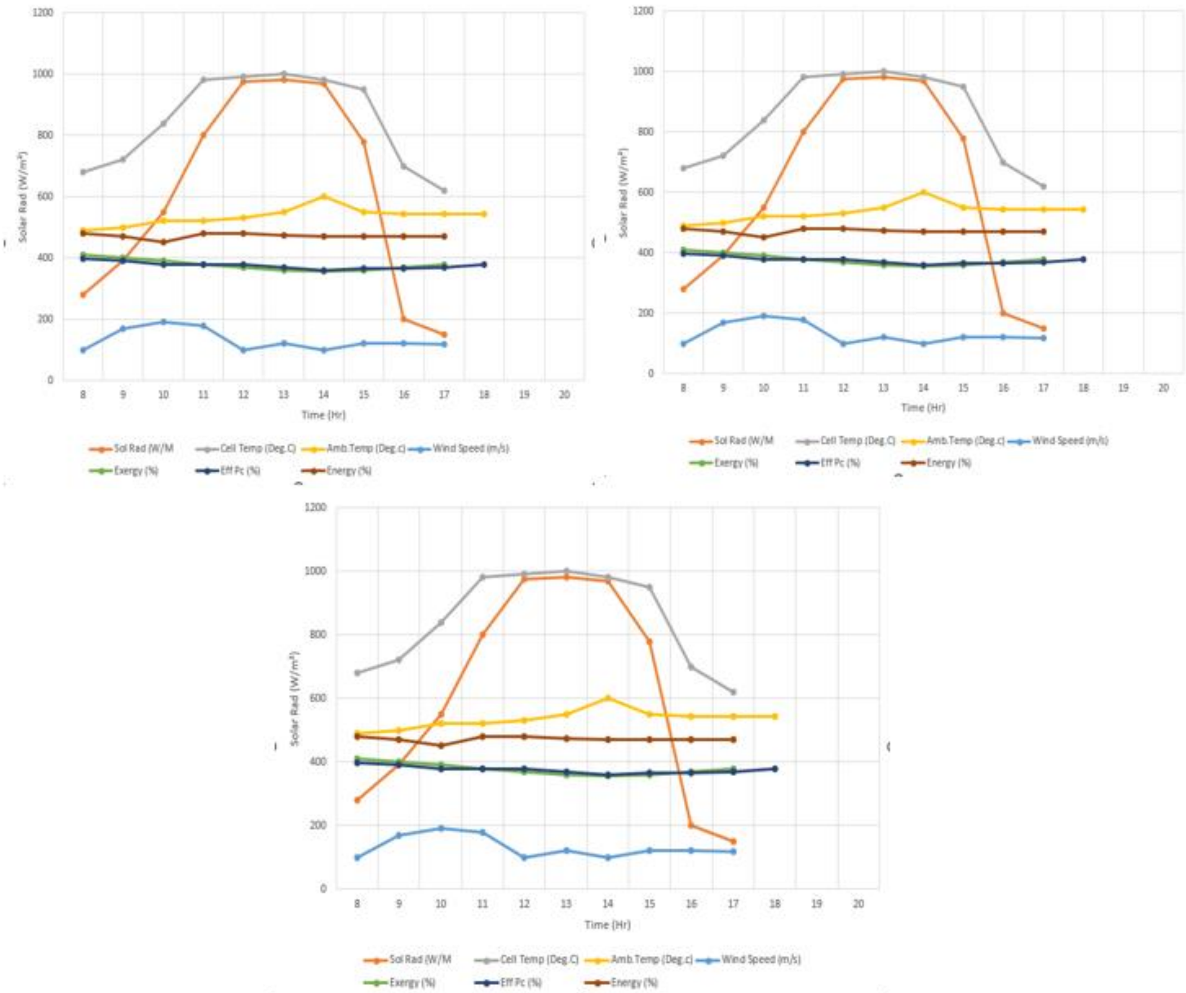

Figure 2: Time-dependent variations of the parameters for three days of February

It has been perceived from the figures that the solar irradiance varies slowly and reaches the peak value at mid-day and then reduces slowly during afternoon. Therefore, the efficiencies have been observed to be changing for the entire day. Therefore, the disparities of all these three efficiencies have been found to have an inverse proportional relationship between solar radiation and the temperature of the solar cell.

The growth in solar cell temperature significantly influences the output of the solar photovoltaic modules. The exergy efficiency fluctuates more often than that of energy efficiency when the wind speed increases beyond the cut-in speed. During day time, the energy efficiency rises more compared to the exergy efficiency. From the first law of thermodynamics the energy efficiency indicates the quantity of energy rather than the quality of energy. The power conversion, average energy, and exergy efficiencies are found to be 13.15%, 18.11%, and 13.05% respectively for January month.

The same type of change has occurred in all the parameters which are described in figure 2. There is less fluctuation in the month of February compared to the month of January. Also, the average energy, power conversion, and exergy efficiencies for the month of February have been found to be 18.75%, 13.68%, and 13.52%. From figures 1 and 2, it is also evident that all the efficiencies for February are higher than those in January.

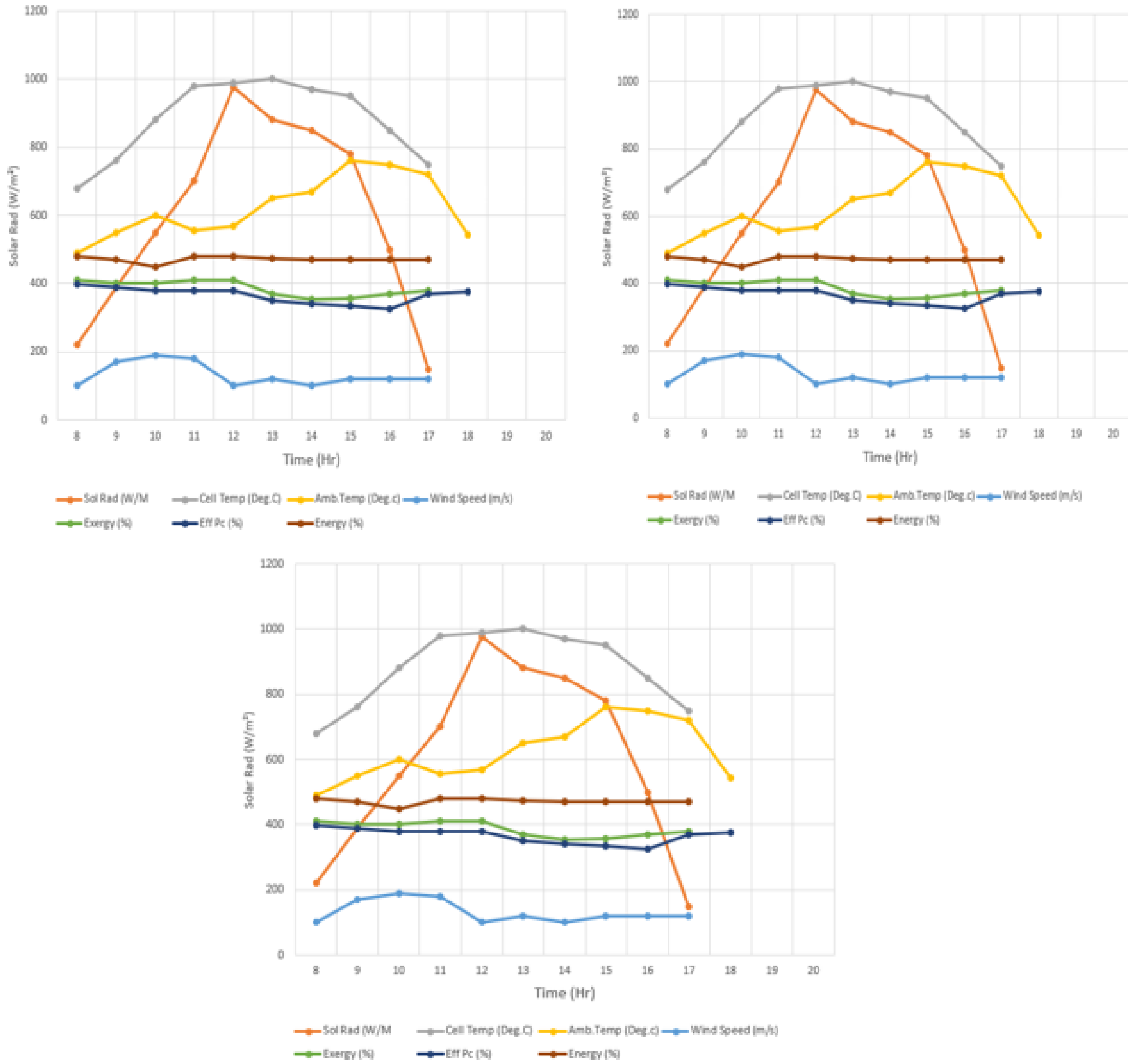

Figure 3: Time-dependent variations of the parameters for three days of April

Furthermore, the energy efficiency and power exchange efficiency of April month are higher in magnitude as compared to the month of May. Likewise, the oscillation in the exergy efficiency and the energy efficiency during 10.30–3.00 hrs, is found to increase as compared to that of 11.30- 01.30 hrs, during the May month that is expressed in terms of ambient air temperature, solar cell temperature, and wind speed as mentioned in the next sections. The power conversion, average energy, and exergy efficiency are 11.57%, 17.27%, and 10.00% for April, but they are around 11.71%, 6.74%, and 10.11% for May.

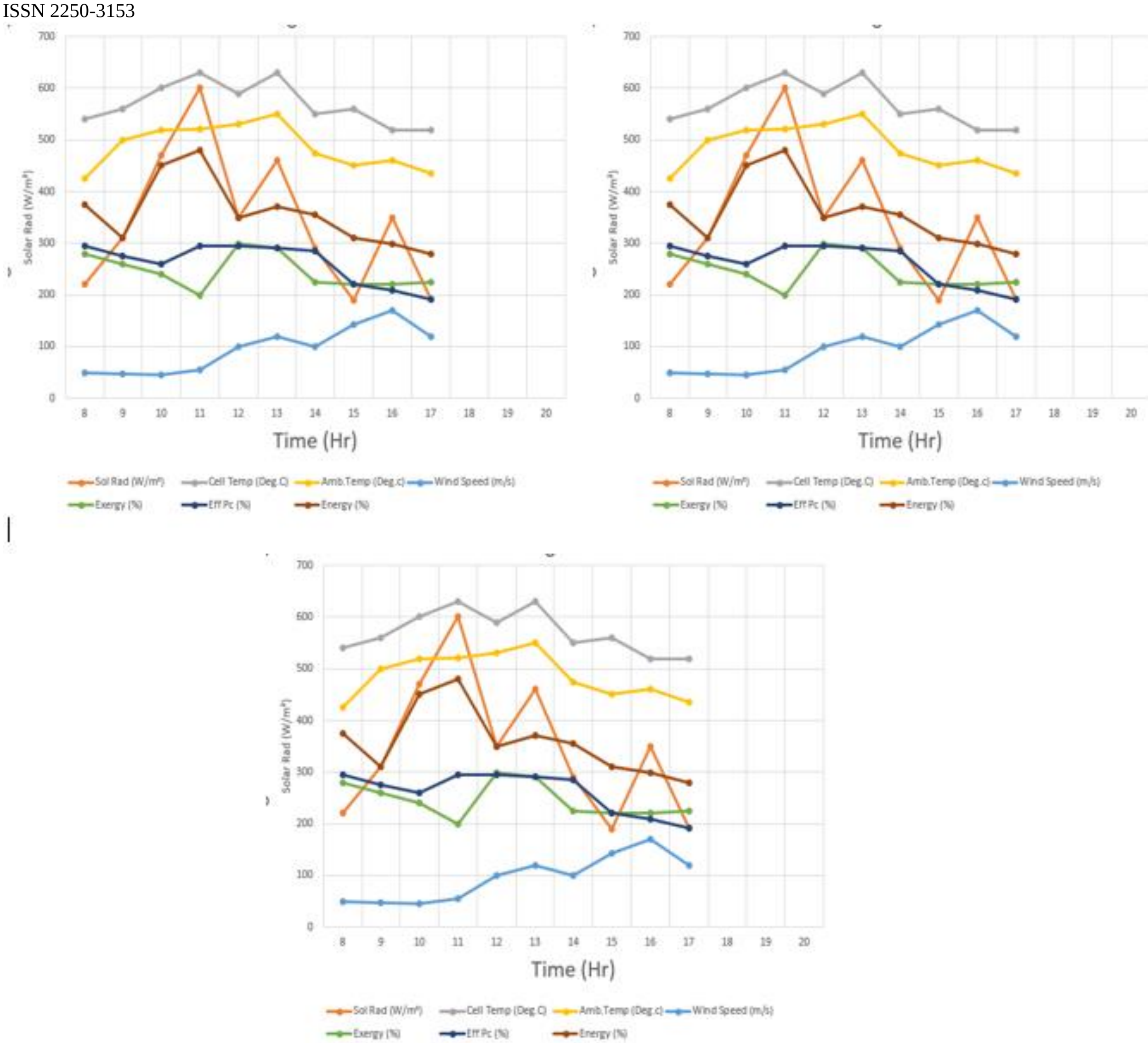

Figure 4: Time-dependent variations of the parameters for three days of May

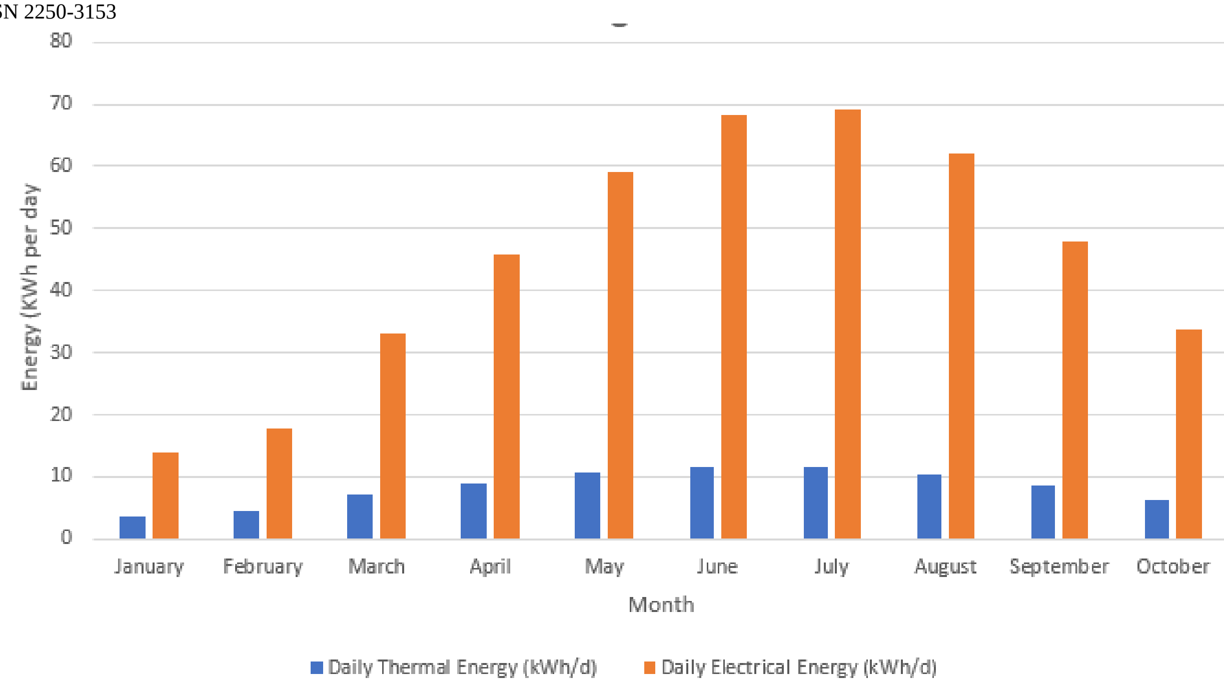

Figure 5: The daily average monthly total produced Electrical and Thermal Energy

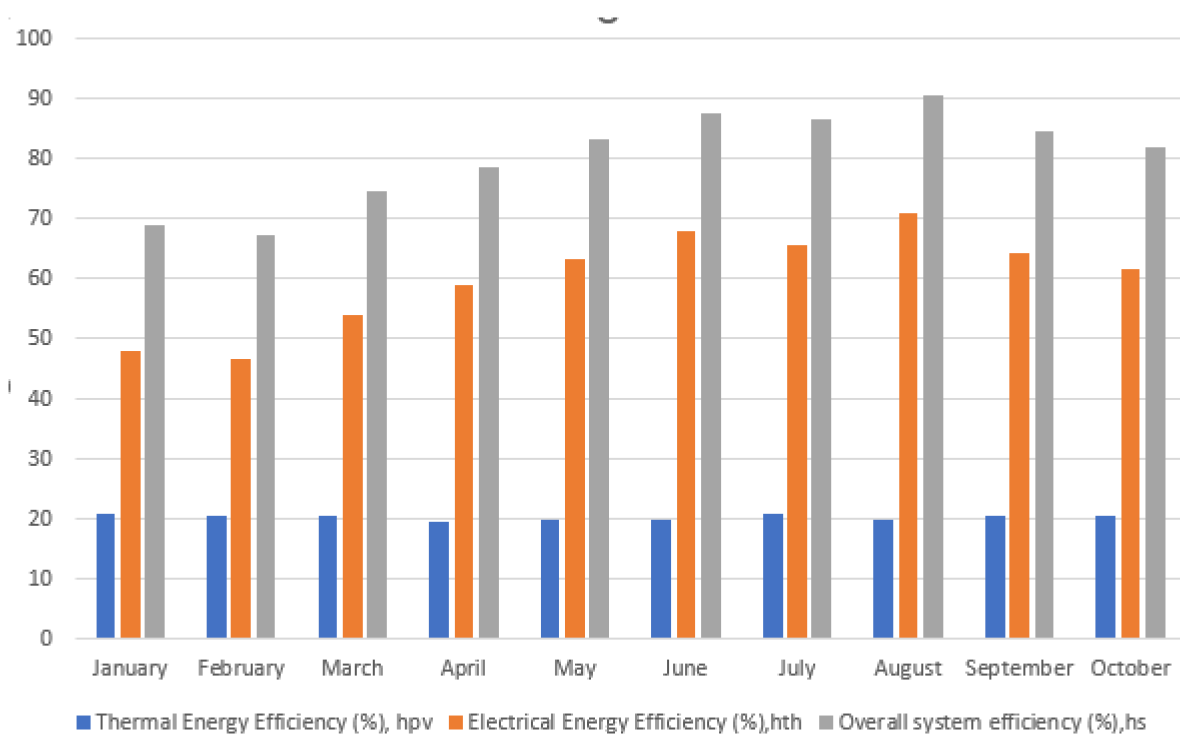

Figure 6: Efficiency Analysis of the system

The shift in solar irradiance and three types of efficiencies versus experimental time duration for the Monocrystalline photovoltaic module during the months of July and August have been depicted in figures 5 and 6 respectively. It has been clearly demonstrated that a severe depression has occurred in all three efficiencies at 11.20 A.M. for the month of July and at around 9.30 A.M. for the month of

August and again at around 3.00 P.M. The sharp fall in solar radiation at that particular instant produces a sudden dip in, efficiencies, thereby resulting in a sharp decrease of output to input ratios. The efficiencies of power exchange, energy, and exergy are 16.22%, 11.31%, and 10.70% respectively for July month, but they are in the range of 11.12%, 16.30%, and 9.03% respectively for August month.

IV. Conclusions

The performance analysis based on energy and exegetic analysis of polycrystalline solar photovoltaic modules has been carried out during specific months of the year 2022. Due to the irregular manner of wind speed and solar radiation, there is a greater variance in all the efficiencies during different months. From the results of different analyses from the graph, evidence shows that the efficiencies are attaining their highest values during the month of February 2022, while the lowest value is attained during the month of August 2022. Consequently, the performance of the Monocrystalline silicon photovoltaic panels has been observed to be highest in the month of February. In this paper, the data and performance analysis is done by using the PV SIM model for the solar PV module. It is clearly observed from the simulation results, that the efficiency is higher in the months of the dry season when compared to the months of the wet season. Additionally, it has also been found that it is rewarding to employ PV SIM compared to the traditional methodologies because of its betterment in simplicity, speed, and accuracy.

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AUTHORS

First Author – David Kibirige, Department of Physical Sciences, School of Natural and Applied Sciences, Kampala International University Uganda.
Second Author – Afam Uzorka, Department of Physical Sciences, School of Natural and Applied Sciences, Kampala International University Uganda
Third Author – Ukagwu Kelechi John, Department of Electrical, Telecommunication and Computer Engineering, School of Engineering and Applied Sciences, Kampala International University Uganda
Fourth Author – Mustafa Mundu Muhamad, Department of Electrical, Telecommunication and Computer Engineering, School of Engineering and Applied Sciences, Kampala International University Uganda

Correspondence Author – Afam Uzorka, Department of Physical Sciences, School of Natural and Applied Sciences, Kampala International University Uganda.