Exergy Analysis of the Major Componets of a Stand-alone Solar-pv Module System for Power Generation

Izu Godstime*

Master of Engineering, Federal University of Petroleum Resources, Nigeria

***Corresponding Author:** Izu Godstime, Master of Engineering, Federal University of Petroleum Resources, Nigeria.

Abstract

This study presents a systemized approach that meticulously examines and gives a comprehensive analysis of exergetic performances of the major components of a stand-alone solar PV system for power generation for various applications. The research gives an all-inclusive analysis of exergy of a solar PV system, focusing on the assessment and evaluation of the performance metrics of its main components such the solar panel, inverter, battery, and solar charge controller. To provide a greater insight and an in-depth understanding of the system's exergy, a selected number of exergy parameters were considered, including exergy production, exergy loss, exergy destruction, exergy destruction ratio, exergy efficiency, energy efficiency, exergy sustainability potential and exergy improvement index. These parameters were chosen because of their ability to give analytical integrity to the system being investigated. The analysis reveals that the solar panel has low exergy efficiency, low exergy sustainability and a high exergy destruction metrics of 31.95%, 1.35 and 68.89% respectively. The solar panel has also been identified as the main source of exergy losses, accounting for 10.1% of the total exergy loss and destruction with 99.5% exergy improvement potential. These descriptive metrics suggest a considerable prospect for optimization and improvement. Comparatively, the battery, inverter, and solar charge controller reveal relatively high exergy efficiencies of 87.95%, 86.00%, and 84.22%, respectively with good sustainability indexes. Conclusively, the findings reveal that optimizing the solar panel can substantially improve the overall system performance and sustainability. No doubt, this study has given valuable approaches required to improve the efficiency, sustainability and performance of the solar PV system.

Keywords: Energy, Exergy, Sustainability, Exergy Destruction, Improvement Potential, PV Module, Efficiency, Optimization

Introduction

For decades, the world relied on the generation of energy from conventional coal, crude oil, wood and others. Thought these sources generated the required energy for the intended purposes, they also left indelible marks of damage on the ecologically habitable home of man or the ecosystem. Oil spillages which destroyed crops and damage to aquatic lives, climate chang and the depletion of the ozone layer are the visible reminders and testimonies of the explorative and exploitative activities of man on natural resources; making the galactically habitable zone (earth) unsafe humans, animals and others. Man, now lives under the continuous fear of being destroyed by the damage caused by him. Common examples are fear of earthquakes resulting from crude oil extraction, ozone depletion due to chlorine molecules, radiations due to radioactive material, just to mention a few. etc.

In recent years, technological advancement and industrial growth and upsurge of economic activities have put a substantial amount of pressure on energy, resulting into energy crisis which ravage most economies of the world. The realization for the need for alternate energy source has pushed to look for other sources such as solar, wind, hydrogen, geothermal and others. Thus, the transition to a greener or cleaner energy have become a major policy in the agendas of the government of most countries of the world today. This therefore, formed the basis for this research. Renewable energy such as solar has become one of the most sorts for in recent years due to its ecosystem preservation potentials and energy sustainability propensity. Hence, this research is a strong support for the world's advocacy for green energy. Thus, presented here is the exergy analysis of the major components of a stand-alone solar PV module system for power generation. This research is posed to delve into a meticulous analysis of the components in order to identify the hotspots area or component with the highest inefficiency metric so that remedial measures can be adopted such

improved design, optimization, etc.

Literature Review

A recent study was conducted to assess "Energy and exergy analysis of hybrid photovoltaic thermal solar system under climatic condition of North Iraq." The study focuses on an elaborate assessment of a hybrid of photovoltaic thermal PVT system for the purpose of identifying the actions of climatic operating characteristics on the thermal efficiencies of the system being analyzed. The results of the analysis showed that the thermal efficiency spans over a range of 25% to 58% while the electrical efficiency covers the range of 12% to 16%. The thermal and exegetic efficiencies metrics fall in the range of 2% to 7% and 10% to 18% repetitively [1].

Considering exergy and energy analysis methods as the benchmark for a robust evaluation, a comprehensive study was conducted on a thermal spray process technique which encompasses energy intensive manufacturing process, focusing exergy destruction as the indicators. This study was intended to highlight the comparative advantages between energy and exergy analysis. The study concluded by establishing the advantages of the exergy analysis technique over the convention energy efficiency evaluation by validating the results of the thermal spray processes [2].

In another study, "the exergy and energy and the mathematical modelling of a cassava starch drying using solar dryer" was presented. The study focused on a series of drying experiment to observe the moisture content of cassava over a given period of time and at a specified temperature range. The results revealed that overall energy efficiency of the dryer was 20.82% obtained at a temperature of 600c. Also, the maximum energy efficiency of the system was found to be 27%. Though the exergetic flow during the process depended on the solar radiation, the exergetic efficiency range spanned over 25.1% to 73.8%. In the study, the relevant mathematical model that adequately capture the system's performance were duly established. Calculated parameters such as effective diffusivity constant and activation energy were $3 \times 10\text{-}10m2$ and 15.3kj/mole respectively at a temperature range of 50-600c [3].

In research conducted, the performance analysis of micro-solar tri-generation system that meet an off-grid single-family lodging was presented. By definition, the system analyzed is plant that is designed to generate electric power, domestic hot water and provide cooling at the same time. The analyses showed that the system possessed overall thermal energy efficiency of 50.53% while the energy extracted from the hot water stands at 3777.5w. The generated electrical power is 2984.6w while the coefficient of performance is 0.6152. The system exergy efficiency showed a metric of 36.88%. The electrical exergy and the exergy generated by the hot water are 2984.6w and 234.3w respectively. Refrigeration extraction produced an exergy of 91.22w [4].

This study presented a novel review of the exergy analyses of several renewable energy system. The renewable energy resources covered were solar wind, geothermal, biomass and others. In the study, the general relations involving exergy production, exergy destruction ratio, exergy efficiency and other relevant equations were established [5].

In turkey, a group of researchers embarked on study proposed to establish the comparative advantage of energy and exergy analyses. The system considered is a heating plant in a multi-purpose building (shopping centre) that requires heating in an area of 80000m2 in Ankara, Turkey. Data spanning over three years from this building were used in the analyses. The conducted energy analysis showed that the boiler has the highest efficiency. However, an exergy analysis proved otherwise, showing that exergy analysis is more reliable for the assessment of the efficiencies of energy systems Exergy analysis is useful for the assessment of systems in which energy transformation takes, making it possible to identify component within the system that exhibit high irreversiblities that lead to the destruction of exergy or useful work [6]. In a study, exergy analyses were conducted to evaluate each component in terms of exergy destruction, exergy destruction ratio, exergy efficiency and others. The results from these evaluations provided the benchmark for decision taken in terms of system optimization required for the overall improvement of the system. The thermodynamic systems considered in this sturdy are chemical reactors, heat exchangers and turbomachines [7].

Energy, exergy and exegoenvironmental analysis of a proposed novel hybrid system was conducted to determine the efficiency, feasibility and the environmental effects of the system in Tehran. The analysis results showed the energy and exergy efficiencies of this hybrid system spanned from 24.7% and 23% to 9.1% and 8%, respectively. The estimated payback period of the system is approximately 21years [8].

In 2018, a group of researchers embarked on a study involving exergy analysis of a hybrid solar-fossil fuel power plant. The study focused on the exergy analysis, energy analysis and the mathematical modeling of a 35MW solar fossil fuel power plant, analyzing the details on the losses of energy and exergy across the different components of the system. From the analysis, the researchers found out that the maximum exergy loss occurs in the collector while the maximum energy loss takes place in the condenser. That analysis also reveals that 47% of the total energy loss takes place in the condenser. The collector and boiler are the chief components that waste energy, amounting to 68.32% of the total exergy loss. Exergy and energy efficiency variation metrics are discovered to be 32.7% and 23% at 12am [9].

In an article published in a journal entitled "Fundamentals of Renewable Energy and Applications" Mei Gong and Göran Wall conducted a study on the life cycle exergy analysis [LCEA] of solar energy system. This methodology is the one

that combines life analysis with exergy to assess the performance metrics of energy system, providing a remarkable visualization of the flow of exergy spanning over the entire life of the system being investigated. The analyzed system showed a payback period of exergy and energy of 15.4 and 3.5 years respectively [10].

In 2022, a highly motivated team of researchers delved into a review of a selected literatures of the last six years that discussed the development of exergy in flat plate solar collectors. Having examined forty innovative articles relevant to the issue, they presented a data matrix that details the formulas and factors that defines exergy in addition to the theoretical designs of the collector and working fluid employed in the flat solar collector. The result table provide a broad and robust insight into the most adopted formula for exergy efficiency, providing the yardstick for decision making [11].

In recent research conducted in 2021, a team of researchers presented a study that analyzed the dynamic exergy and exergo-economic analysis of a cogeneration-based hybrid renewable energy system. Considered system consisted of photovoltaic and solar collector and biomass powered Stirling engine micro-CHP with thermal energy storage. The study defined the particular costs of different energy product from the system using exergo-economic analysis. The exergy variation of the system was found to be 13% to 16% and the payback time was 19.3years [12].

Modeling and optimization of energy and exergy parameters of a Hybrid-Solar dryer for basil leaf drying using [RSM] study was present by a team of researchers. In this study, experiment was performed on the drying of basil leaves under varied temperatures of 40oc, 55oc and 70oc with corresponding three bed thickness of 2, 4 and 6cm respectively. The results obtained provided the bases for the determination of the optimum drying condition of the leaf. This showed a temperature of 63.8oC ta bed thickness of 2 cm. The thermodynamic parameters were optimized using "response surface method [RSM]" considering the "central composite design, [CCD]" and the "design function [DF], to maximize the rate of drying [13].

A team of researchers delved into a study involving the exergy analysis of solar dryer that has a supplementary backup dryer known as incinerator. The analyzed system was a fabricated solar dryer with a backup incinerator integrated for the purpose of improving the efficiency of the drying rate of a varied agricultural product. The drying plant has three sub-unit. First is the collector, the second is the drying chamber and the third is the incinerator. To experiment the exergy performance of the fabricated dryer, 1000g of chill pepper was dried using the solar drying aspect of the system, then the same quantity of specimen was experimented upon using the incinerator dry unit. The comparative drying efficiency and their respective exergy efficiencies were established [14].

In 2021, International journal of multidisciplinary sciences and engineering published an article entitled "exergy concepts and its characteristics. This study delved into the basic concepts of exergy, focusing on exergy applications in various field and established the distinction between energy and exergy analyses. The different forms of exergies were discussed in this research [15].

Methodology

This research adopted a systemized exergy analysis technique based on the second law of thermodynamic to assess and evaluate the exergy and the sustainability performance metrics of a stand-alone solar photovoltaic system by means of an advanced simulation tool known as Aspen plus simulation software which aided a robust modeling and simulation of the thermodynamic characteristics of the system.

This study employed a comprehensive exergy analysis approach to evaluate the performance and sustainability of a solar photovoltaic (PV) system. The analysis was conducted using Aspen Plus simulation software, which provided a robust platform for modeling and simulating the thermodynamic behavior of the system. The simulation setup incorporated solar panel, inverter, battery and solar charge controller. The data employed are shown in the following tables 3.1 to 3.4

Technical variable	Data
Solar PV type	CS6K-285M-FG
Panel cell type	Monocrystalline
Nominal Max Power (P_{max})	285 W
Azimuth Angle (Degree) (W of S)	0
Derating Factor (%)	88
Ground Reflectance (%)	20
Solar Tracking system (Nil)	Nil
Lifetime (Years)	25
Max. Series Fuse Rating	15A
STC Rating (W)	285
Efficiency (%)	17.33

Open circuit voltage (V_{oc})	38.6 V
Short circuit current (I_{sc})	9.51 A
Optimum operating voltage (V_{mp})	31.7 V
Optimum operating current (I_{mp})	8.98 A
Nominal Cell Operating Temperature (NOCT)	45°C
Number of Cells	60 (6 x10)
Parallel String	11
Max. System Voltage	1500 (IEC) or 1000 V (UL)
Temperature coefficient (P_{max})	−0.41%/K
Temperature coefficient (V_{oc})	−0.12 V/K
Temperature coefficient (I_{sc})	−0.053%/K

Source (Podder et al., 2021)

Table 3.1: The Technical Specification of Solar PV Panel Data

Kinetic Battery Model	Enersys PowerSafe SBS 900 battery
Nominal Voltage (V)	12
Nominal Capacity (kWh)	12.1
Maximum (Ah)	1010
Capacity Ratio	0.157
Rate Constant (1/hr.)	4.62
Roundtrip efficiency (%)	97
Maximum Charge current (I_{mc})	900 A
Maximum discharge current (I_{md})	720 A
Maximum charge rate (A/Ah)	1
Length	5.70 in
Length	5.70 in
Height	8.10 in
Depth	27.4 in
Typical Weight Unpacked:	110 lbs
Terminal Type	M10F
Volume	2.19 gal
Weight	23.7 lbs
Pure Acid (H_2SO_4) Acid:	
Volume	0.62 gal
Weight	9.41 lbs
Lead Weight (per cell)	73.9 lbs

Source: (Power Safe® SBS Batteries, 2024)

Table 3.2: Technical Specifications of Battery

SOLAR CHARGE CONTROLLER PARAMETERS	TECHINCAL SPECIFICATION
Ratings	12/24(Auto-work)
Ephc-5	12V or12/24V (Auto-work)
Ephc-10	12v or 12/24V (Auto-work)
Regulation point	6Ma (maximum)
Self-consumption	11.1V
Low voltage disconnection	For wire size, up to 2.5mm2
Terminals	Series PWM 4 Stages bulk, boost and float
Type of charging	250g
Temperature	-35oc to +55oc

Electronic protection	Reverse polarity-solar, load and battery reverse current at night, High voltage-load lightning, solar, load and battery, 100% non-condensing
Humidity	Ip 22
Enclose	ABC CE World
Case	CE World
Compliance	Green-Yellow-Red: Battery levels
Indicator	Red: Low voltage warning and disconnection All 3 LEDs Blind: To show mistakes

<div align="center">Source (Syafaruddin, 2014)</div>

<div align="center">Table 3.3. Technical Specification of Solar Charge Controller</div>

SOLAR INVERTER PARAMETERS	TECHNICAL SPECFICATION
Inverter capacity	50KW
Input side [DC]	1000V
Maximum voltage	610Vdc
Rated voltage	51200W
Voltage range	110A
Maximum current	10.2A
Output side [AC]	3-Phases
Rated AC power	50000W
AC voltage range	320-480V
Output current	77A
Efficiency	89.30
Weight	0.095g

<div align="center">Source (ResearchGate)</div>

<div align="center">Table 3.4: Inverter Specifications</div>

MONTH	CLEARNESS INDEX	DAILY RADIATION (KWH/M^2/DAY)
Jan	0.538	5.076
Feb	0.508	5.068
Mar	0.496	5.162
Apr	0.467	4.864
May	0.454	4.589
Jun	0.429	4.23
Jul	0.357	3.551
Aug	0.36	3.684
Sep	0.405	4.183
Oct	0.463	4.639
Nov	0.537	5.102
Dec	0.546	5.036

<div align="center">Table 3.5: Clearness Index and Daily Sun's Radiation</div>

Solar PV System Mathematical Modeling

This section delves into the mathematical modeling of solar PV system being analyzed. Developing a mathematical model that adequately capture the complex interactions between solar irradiance and the solar panels plus other components and their contribution to the process of power generation, will provide a greater insight of the system working principles and simplify the analysis. The table below presents the summary of all appropriate equations that satisfactorily captures and modeled system.

S/N	EXERGY PARAMETER	MODEL FORMULATION	REFERENCES
1.	Mass balance	$\sum \dot{m}_{in} = \sum \dot{m}_{Out}$	(Yan et al., 2020).
2.	Energy balance	$\sum E_{in} = \sum E_{Out}$	(Yan et al., 2020).
3.	Energy balance for transfer of Matter	$\sum \dot{E}_{in} - \sum \dot{E}_{Out} + \sum Q_{in} - W_{Out} = 0$	(Güémez & Fiolhais, 2016)
4.	Overall exergy for typical system	$E_X = E_X{}^{PHY} + E_X{}^{KE} + E_X{}^{PE} + E_X{}^{CHM}$	(Rosen & Bulucea, 2009)
5.	General exergy balanced equation	$\sum Ex_{in} - \sum Ex_{Out} + \sum Ex_Q - Ex_W - Ex_I = 0$	(Rosen & Bulucea, 2009)
6.	Exergy efficiency	$\psi_{ex} = \dfrac{Ex_{out}}{Ex_{in}}$	(Aigba et al., 2022).
7.	Input exergy of hybrid system	$Ex_{in} = mC_P \left[(T_{in} - T_\infty) - T_\infty In \left(\dfrac{T_{in}}{T_\infty} \right) \right]$	(Barcia & Gorozabel-Chata, 2022; Liu et al., 2022)
8.	Output exergy of hybrid system	$Ex_{Out} = mC_P \left[(T_{Out} - T_\infty) - T_\infty In \left(\dfrac{T_{Out}}{T_\infty} \right) \right]$	(Barcia & Gorozabel-Chata, 2022; Liu et al., 2022)
9.	Exergy loss	$Ex_{loss\ or\ destroyed} = Ex_{in} - Ex_{out}$	
10.	Solar PV energy output	$\dot{E}_{Out} = \dot{E}_{ele} + \dot{E}_{therm} = V_{OC} + Q$	(Kalogirou et al.,2016)
11.	Solar PV energy output	$Ex_{Out} = Ex_{ele} + Ex_{therm} + Ex_D$ $= Ex_{ele} + Ex_I$	(Green, 2009)
12	Electrical exergy of solar PV	$Ex_{ele} = V_{oc} * I_{sc} - (V_{oc} * I_{sc} - V_{max} * I_{max})$	(Jensen et al., 2014). (Jensen et al., 1998
13.	Maximum electrical PV power output	$Ex_{ele} = W_{PV} = V_{max} * I_{max}$	(Saloux et al., 2013 and Green, 2009
14.	Fill factor	$FF = \dfrac{P_{max}}{V_{OC} * I_{SC}} = \dfrac{V_{max} * I_{max}}{V_{OC} * I_{SC}}$	(Skoplaki et al. 2009
15.	Solar PV thermal exergy	$Ex_{therm} = Q \left(1 - \dfrac{T_{amb}}{T_{PV}} \right)$	(Farahat et al., 2009 & Kalogirou et al., 2016)
16.	System's heat dissipation	$Q = h_{CR} * A_{PV} * (T_{PV} - T_{amb})$	(Farahat et al., 2009 & Kalogirou et al., 2016)
17.	Heat transfer coefficient	$Q = h_{CR} * A_{PV} * (T_{PV} - T_{amb})$	(Farahat et al., 2009 & Kalogirou et al., 2016)

18.	Exergy of solar PV system	Ex_{PV} $= V_{max} * I_{max}$ $- \left(1 - \frac{T_{amb}}{T_{PV}}\right)\left[\begin{matrix} h_{conv}A_{PV} \\ * (T_{PV} - T_{amb}) \end{matrix}\right]$	(Underwood, 2001)
19.	Convective heat transfer coefficient	$h_{conv} = 2.8 + 3W_s$	(Farahat et al., 2009 & Kalogirou et al., 2016
20	Radiative heat transfer coefficient	$h_{rad} = \varepsilon\sigma(T_{sky} + T_{PV})(T^2{}_{sky} + T^2{}_{PV})$	(Farahat et al., 2009 & Kalogirou et al., 2016
21	Temperature of sky	$T_{sky} = T_{amb} - 6$.	(Farahat et al., 2009 & Kalogirou et al., 2016
22.	Maximum electrical power	$P_{max} = Ex_{ele}$	Rosen & Bulucea, 2009)
23	System's energy efficiency	$\eta_{\dot{E}} = \frac{\dot{E}_{Out}}{\dot{E}_{in}} = \frac{V_{OC} * I_{SC}}{A_{PV} * S_T}$	(Rad et al., 2020, Panwar & Jadhav 2018, & Sahin et al., 2007).
24	Power conversion efficiency	$\eta_{PC} = \frac{E_L}{A_{PV} * S_T} = \frac{V_m * I_m}{A_{PV} * S_T}$ $= \frac{V_{OC} * I_{SC} * FF}{A_{PV} * S_T}$	(Panwar & Jadhav, 2018)
25	Exergy input of solar PV system	$Ex_{in} = A_{PV} * S_T$ $* \left[1 - \frac{4}{3}\left(\frac{T_{amb}}{T_{sun}}\right) + \frac{1}{3}\left(\frac{T_{amb}}{T_{sun}}\right)^4\right]$	(Kalogirou et al., 2016)
26.	Exergy of solar irradiance	$Ex_{Solar} = \left(1 - \frac{T_{amb}}{T_{Sun}}\right)[A_{PV}.S_T]$	(Green, 2003)
27	Total exergy of solar PV system	$\psi_{Ex} = \frac{Ex_{Output}}{Ex_{Input}} = 1 - \frac{\sum(Ex_L + Ex_D)}{Ex_{Solar}}$	(Bejan, 1988)
28.	Optical losses which occur on the surface of the PV array	$Ex_{D,opt} = S_T * (1 - (\tau\alpha))\left(1 - \frac{T_{amb}}{T_{PV}}\right)$	(Akyüz et al., 2012).
29.	Sun and solar PV temperature difference	$Ex_{D,\Delta T_{Sun}} = S_T * T_{amb}(\tau\alpha)\left(\frac{1}{T_{PV}} - \frac{1}{T_{Sun}}\right)$	(Farahat et al., 2009)
30	Specific heat capacity for silicon solar cells	$C_P = 0.844 + 1.18 * 10^{-4} T_{PV} - 1.55 * T_{PV}^{-2}$	(Farahat et al., 2009)

31	Exergetic destruction due to temperature variation in PV array	$$Ex_{D,\Delta T_{Var}} = \frac{\dot{m}_{PV} * C_P * T_{amb}}{\Delta t} * \left(ln\left(\frac{T_{PV}}{T_{amb}}\right) - \frac{(T_{PV} - T_{amb})}{T_{PV}} \right)$$	(Abushgair, 2021)
32	Exergetic destruction caused by the irreversibilites associated with electrical energy	$$Ex_{D,ele} = V_{oc} * I_{sc} - V_{max} * I_{max}$$	(Reddy et al., 2012)
33	The overall exergetic efficiency of the solar PV	$$\psi_{Ex} = 1 - \frac{\sum(Ex_L + Ex_{D,opt} + Ex_{D,\Delta T_{Sun}} + Ex_{D,\Delta T_{Var}} +}{A_{PV} * G * \left[1 - \frac{4}{3}\left(\frac{T_{amb}}{T_{sun}}\right) + \frac{1}{3}\left(\frac{T_{amb}}{T_{sun}}\right)\right]}$$	(Rosen & Bulucea, 2009
34	Exergy loss	$$Ex_{Loss} = UA_{PV} * (T_{PV} - T_{amb})\left(1 - \frac{T_{amb}}{T_{PV}}\right)$$	(Farahat et al., (2009).

Table 3.5: Solar PV System Mathematical Model

Thermodynamic Assumptions
- Steady-state conditions were considered
- Temperature distribution is uniform
- Negligible heat transfer between components and surroundings
- Solar irradiance is constant
- Constant ambient temperature
- Ideal gas behavior for air is considered
- No shading or partial shading effects
- Material properties are uniform
- Electrical and thermal properties of materials are constant

Exergy Analytical Focus
The exergy analysis was systematically conducted. It began with the evaluation of thermodynamic properties of the system using Aspen plus. The thermodynamic properties were exergy flows, energy flows, pressure and temperature. Following this was the exergy balance calculations for each component of the system considering exergy input, output, losses and destruction. The components exergy efficiencies were calculated based on exergy input and out of each component. The exergy sustainability index and the improvement potential for each component were also evaluated. The data obtained were carefully analyzed so as to identify the areas of the system that required optimization and improvement potentials. The resulting data provided the bases for the recommendation, improvement and the optimization required to augment the overall system performance and sustainability.

Results and Discussion
This study provides a detailed exergy analysis of a solar photovoltaic (PV) system. It examines how different components perform and how efficiently they convert and utilize energy. The main parts studied include the solar panel, inverter, battery, and solar charge controller. Exergy analysis is a powerful tool because it not only measures how much energy is used but also evaluates the quality of energy throughout the system. This helps identify where energy is lost or wasted. By understanding these losses, engineers and designers can find ways to improve the system's efficiency and make it more sustainable. The results from the analysis reveal clear differences in how each component performs. The data is summarized to show their individual efficiencies, how much exergy they destroy, and their sustainability index. These numbers matter because they show where improvements are most needed. The solar panel has an exergy efficiency of about 31.95%. This means it converts only a small portion of the sunlight's energy into usable electricity.

The rest is lost mainly due to the inherent limits of photovoltaic conversion. The exergy destruction ratio for the solar panel is around 68.89%, the highest among all components. This large percentage indicates that most of the energy input is lost during the conversion process. It highlights the biggest challenge and area for improvement. The solar panel's exergy sustainability index (ESI) is 1.35, reflecting its relatively lower performance and higher environmental impact compared to other parts. In comparison, the inverter shows a much higher exergy efficiency at 86.00%, with a destruction ratio of just 12.15%. This suggests it converts energy more effectively, with fewer losses. The inverter's ESI is 6.23, indicating a much better sustainability record and lower negative impact on the environment. Similarly, the battery performs well, with an exergy efficiency of 87.95%, destruction ratio of 10.45%, and an ESI of 7.15. This means it stores and releases energy with minimal losses and is more environmentally friendly. The solar charge controller also performs well, with an efficiency of 84.22%, destruction ratio of 13.55%, and an ESI of 5.92. Although its efficiency is slightly lower than the inverter and battery, it still manages energy flow effectively. These results highlight that the solar panel is the main source of energy loss in the system. Because of its lower efficiency, it accounts for roughly 68.89% of all exergy destruction within the system. This significant loss results from the physical limits of sunlight-to-electricity conversion and the current design of photovoltaic cells. Despite this challenge, the other components show strong performance, with high efficiencies and low exergy destruction. This indicates that once sunlight is captured, the system's other parts perform well. The exergy sustainability index (ESI) values reveal which parts have better environmental performance. The battery and inverter have the highest ESIs, showing they use energy more sustainably and produce fewer environmental impacts. Their high ESIs suggest they are more efficient in extracting value from available energy and reducing waste. The solar panel's lower ESI points to a need for improvements in how it captures and converts sunlight. Efforts could include developing better materials or optimizing panel design to reduce energy loss. Overall, this exergy analysis offers in-depth insights into system performance. It identifies the solar panel as the main source of inefficiency, signaling where innovation is needed. It also shows that the other components efficiently convert and store energy, contributing to the system's overall performance. Addressing the limitations of the solar panel could lead to significant gains in system efficiency and sustainability. Improving this area could reduce environmental impact and increase energy output, making solar PV systems more reliable and cost-effective in the long run. This analysis provides a clear roadmap for engineers and researchers. By focusing on enhancing the solar panel's efficiency, system designers can boost overall performance. Upgrading components like the PV cells or employing new materials could cut energy losses drastically. These enhancements will not only improve energy conversion but also contribute to a more sustainable future. Every percentage point of increased efficiency can significantly reduce the environmental footprint. The goal remains to develop solar PV systems that make better use of available sunlight while minimizing waste and environmental harm.

EQUIPMENT	EX_{FUEL} (W)	EXP_{ROD} (W)	EX_D (W)	EX_L (W)	EXERGY DESTRUCTION (%)	EX_D RATIO, Y_D (%)	ENERGY EFFICIENCY [%]	Y*D [%]	EXERGY EFFICIENCY [%]	IMPROVEMENT POTENTIAL	ESI
Solar panel	1235.21	182.30	1012.91	1.26	79.01	68.89	26.92	76.89	31.95	732.19	1.35
Inverter	170.93	154.09	1.00	5.84	1.64	3.00	85.60	1.51	86.00	1.29	12.09
Battery	65.22	78.18	1.00	2.54	1.14	3.05	88.00	1.12	87.95	1.03	58.32
Solar charge controller	30.18	27.22	1.00	2.81	1.17	6.98	98.90	1.24	84.22	1.31	14.253

Table 4.0: Solar PV Component Exergy Performance Details

Exergy Production Analysis
The exergy production details of the solar power generation components are depicted in the data shown in table 4.1 below. apparently, the data provides valuable insights into the exergy performance of each component, highlighting the hotspots areas for potential improvement and optimization. The solar panel has the highest exergy production at 182.30 W, as it's the primary component that converts solar energy into electrical energy. The inverter has an exergy production of 154.09 W, which is about 84.5% of the solar panel's output. This suggests that the inverter is efficient in converting DC power from the solar panel to AC power. The battery has an exergy production of 78.18 W, which is about 43% of the solar panel's output. This indicates that the battery is storing and releasing energy, but with some losses. The battery has an exergy production of 78.18 W, representing about 42.9% of the solar panel's output. This is an indication that the battery stores and discharges energy with some losses. The solar charge controller displays the lowest exergy production at 27.22 W, which is about 14.9% of the solar panel's output. This suggests that the solar charge controller is operating at low efficiency, leading to a substantial exergy destruction. Thus, optimizing the solar charge controller can significantly improve the overall efficient of the system. The visual representation is shown in figure 4.1 below.

SOLAR PV COMPONENTS	EXERGY PRODUCTION [EX_{PROD}] (W)
Solar panel	182.30
Inverter	154.09
Battery	78.18
Solar charge controller	27.22

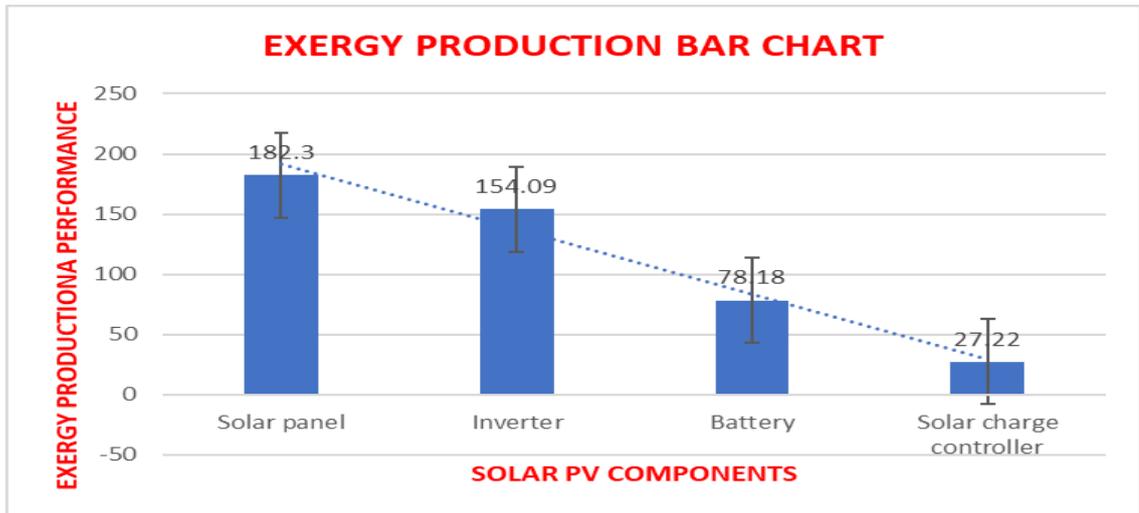**Table 4.1: Exergy Production**

Figure 4.1: Exergy Production Bar Chart

Exergy Destruction Analysis

The exergy destruction specifics of the solar PV components disclose a substantial hotspot area for optimization. The solar panel exhibits the greatest exergy destruction of 1012.91 W, approximately accounting for about 99.7% of the total exergy destroyed. This reveals that the solar panel is the main source of inefficiencies withing the system, and augmenting its design, material, or operating settings could lead to considerable improvements. In contrast, the inverter, battery, and solar charge controller have insignificant exergy destruction values of 1.00 W each, accounting for only about 0.1% of the total exergy destruction each. This indicates that these components are operating relatively efficiently, and optimization efforts should focus on the solar panel to maximize system performance. The large potential difference in terms of exergy destruction existing between the solar panel and the other components shows that, it is the component that requires optimization for the improved performance of the system. This implies that optimizing the solar panel can increase the overall efficiency of the system. To achieve this, thermal management is needed. That is, the solar panel should be equipped with cooling system or proper ventilation that can reduce its temperature as high temperature leads to exergy destruction. Improved solar panel design can also help in improving the solar panel performance. Table4.2 displays the system's exergy destruction metrics while figure 4.2 gives the graphical representation of the analysis.

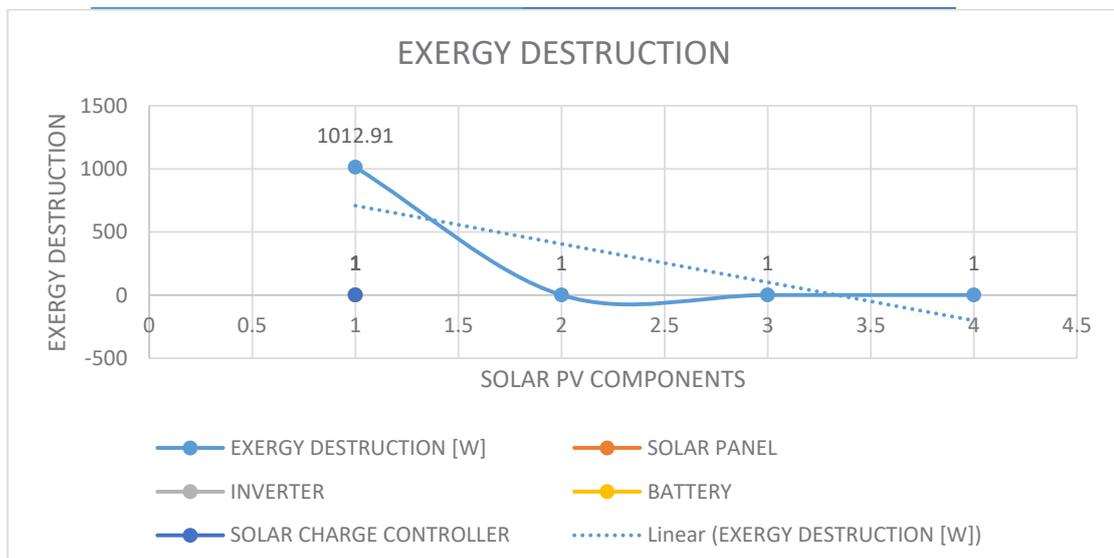| SOLAR PV COMPONENTS	EXERGY DESTRUCTION [EX_D] (W)
Solar panel	1012.91
Inverter	1.00
Battery	1.00
Solar charge controller	1.00

Table 4.2: Exergy Destruction Details

Figure 4.2

Exergy Loss Analysis

The exergy loss details of the solar PV components depicted in table 4.3 below has revealed varying degrees of losses. The inverter displays the highest exergy loss of 5.84 W which approximately accounted for about 46.9% of the total exergy loss. The solar charge controller demonstrated exegetic loss of 2.81 W, amounting to about 22.6% of the total exergy loss. However, the battery exergy loss metrics is 2.54 W, which is an approximately 20.4% of the overall exergy loss. The solar panel displays the least exergy loss of 1.26 W, representing about 10.1% of the total exergy loss. The inverter is the primary source of exergy losses, amounting to approximately 46.9% of the total exergy loss. These results show that the inverter is the main source of exergy losses, and improving its efficiency could lead to substantial improvements. Thus, Optimization efforts should be directed toward improving the efficiency of the inverter so as to reduce losses. The solar charge controller and battery also contribute significantly to exergy losses, and optimizing their performance could lead to further improvements. Visual representation of the analysis is shown in figure 4.3 below.

SOLAR PV COMPONENTS	EXERGY LOSS [EX_L] (W)
Solar panel	1.26
Inverter	5.84
Battery	2.54
Solar charge controller	2.81

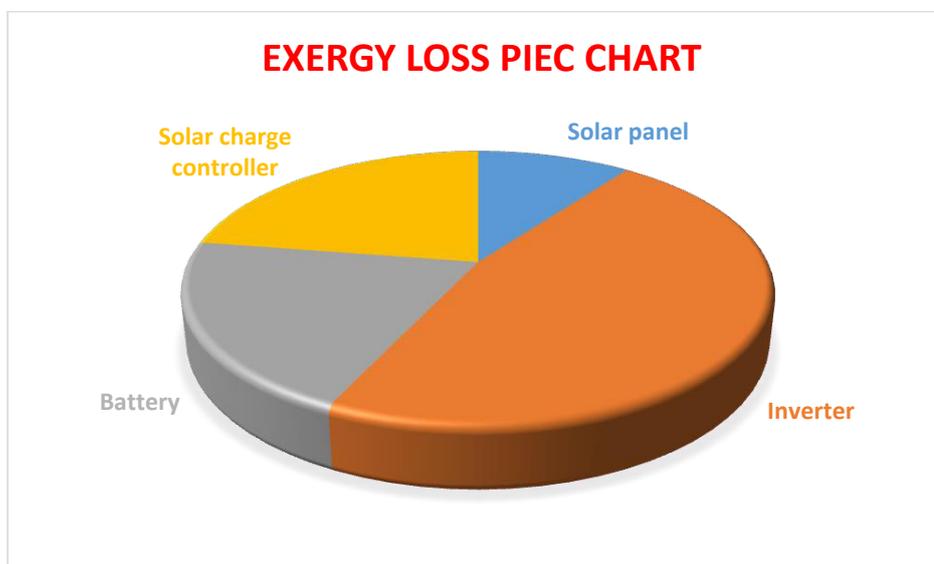**Table 4.3: Exergy Loss Details**

Figure 4.3: Exergy Loss Pie Chart

Exergy Destruction Percentage

Table 4 below presents the details of the amount of exergy destroyed in percentage, giving a greater insight and in-depth understanding of the exergetic analysis of the system under investigation. Deductively, the exergy destruction percentages of the solar PV components have revealed a noteworthy discrepancy in terms of losses. The solar panel, as expected displays the largest percentage of exergy destruction at 79.01%, signifying the prime source of inefficiencies in the system. by contrast, the inverter, battery, and solar charge controller have relatively negligeable exergy destruction percentages of 1.64%, 1.14%, and 1.17%, metrics respectively. These benchmarks advocate the need to direct optimization efforts and focus on the solar panel optimization to ensure the system's overall performance, and ultimately, the efficiency. The pie chart of exergy destruction percentage is shown in figure 4.4 below.

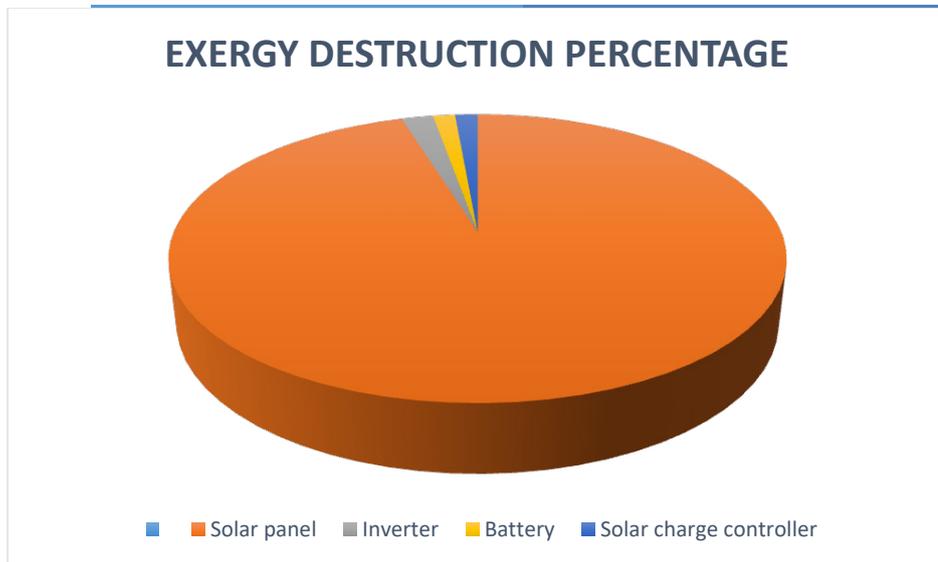| SOLAR PV COMPONENTS	EXERGY DESTRUCTION PERCENTAGE (%)
Solar panel	79.01
Inverter	1.64
Battery	1.14
Solar charge controller	**1.17**

Table 4.4: Percentage of Exergy Destruction

Figure 4.4: Percentage of Exergy Destruction

Exergy Destruction Ratio Analysis

The exergy destruction ratio results presented in table 4.5 had shown the variations in terms of losses across the various components of the system. The solar panel displays a significant exergy destruction ratio of 68.89% and emerged as the principal contributor to exergy destruction within the system. This metric is pointer to the pay closer attention to the optimization of the solar panel it terms of its design, operating conditions and thermal control such as the integration of cooling system or effective ventilation technique geared towards minimizing losses. Comparatively, the solar charge controller exhibited exergy destruction ratio of 6.98%, indicating a significant contribution to exergy destruction. The battery and inverter with exergy destruction metrics of 3.05% and 3.00% respectively, have demonstrated minor contrition to exergy destruction across the system. Exergy destruction ratio graph is shown in figure 4.5, providing a visual illustration of the analysis and a greater insight of exergy destruction in the system.

SOLAR PV COMPONENTS	EXERGY DESTRUCTION RATIO [Y_D](%)
Solar panel	68.89
Inverter	3.00
Battery	3.05
Solar charge controller	6.98

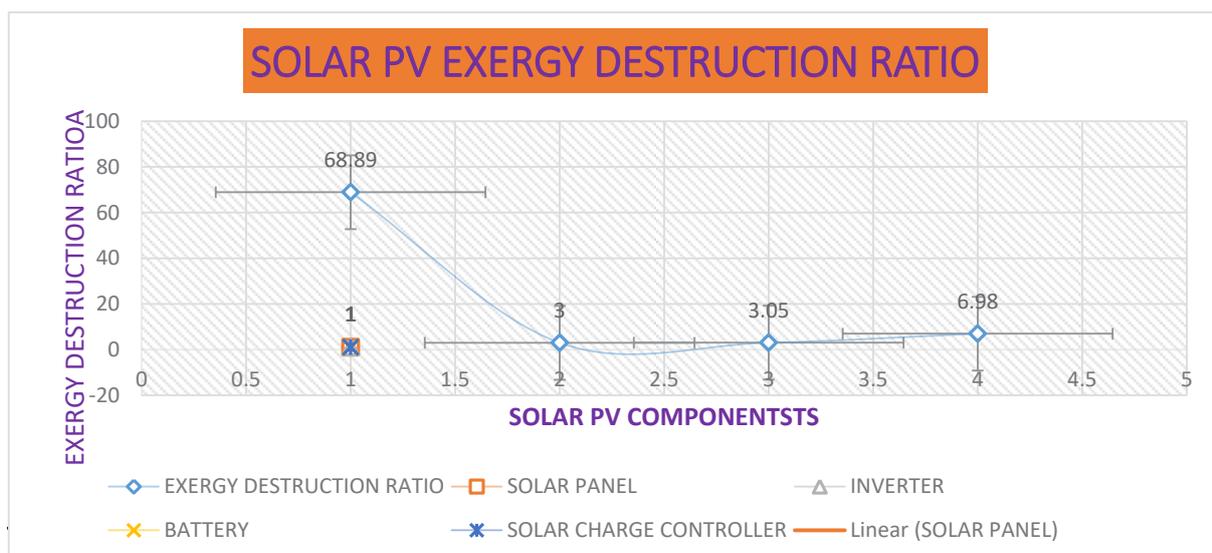**Table 4.5: Exergy Destruction Ratio Details**

Figure 4.5: Exergy Destruction Graph

Energy Efficiency Analysis

Energy efficiency is s thermodynamic metric that describes the system's input and output energy relationship expressed as a percentage. However, in this analysis, the individual component's energy in relation to the total energy is considered as a base for the evaluation of the energy efficiency. The details of energy efficiency of the individual components are shown in table 4.6 below. From the simulation results, the solar charge controller has demonstrated an efficiency of 89.9%, implying it is the most efficient component in the system with minimal losses. The inverter and solar and battery with a percentage metrics of 88% and 85.6% respectively, is an indication that they are operating effectively. The solar panel with an efficiency of 26.92% is a pointer to the direction of inefficiency and the need for its optimization. This will in no doubt offer the beacon of quest for improved system performance. To give a visual aid to the understanding of the system's energy performances, a bar chart is presented in figure 4.6.

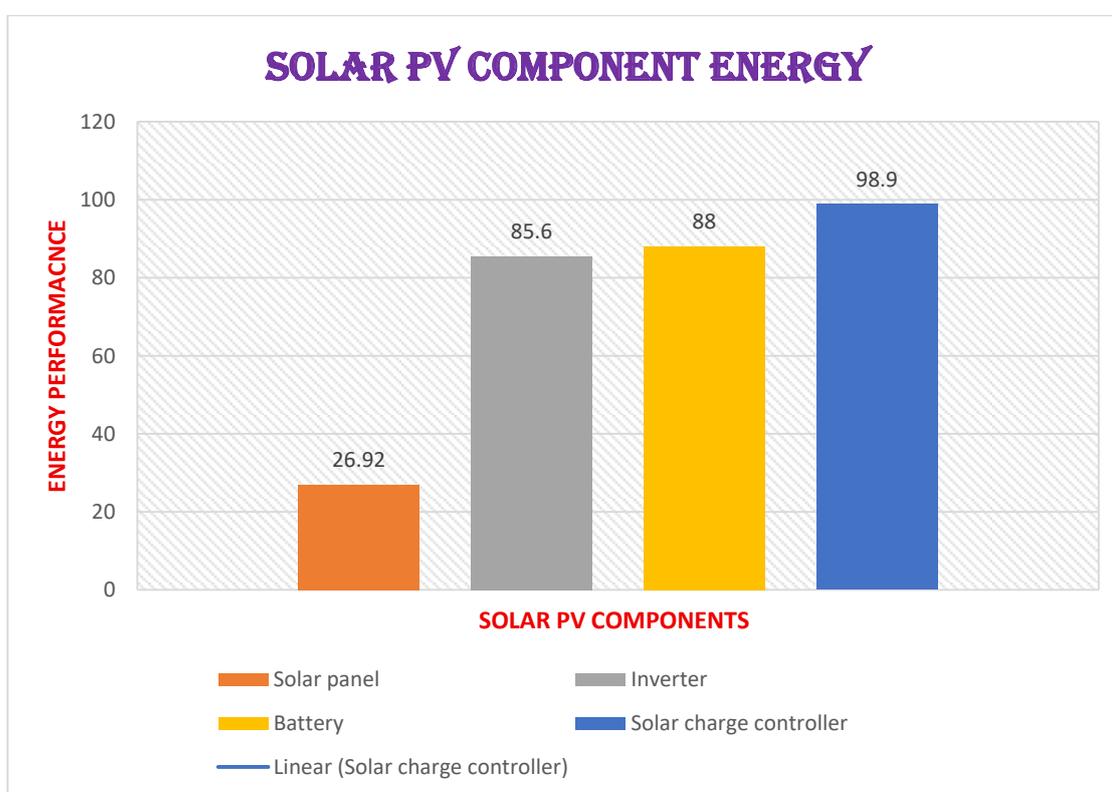| SOLAR PV COMPONENTS	ENERGY EFFICIENCY [%]
Solar panel	26.92
Inverter	85.60
Battery	88.00
Solar charge controller	98.90

Table 4.6: Solar PV Component Energy Efficiency

Figure 4.6: Energy Performance of PV Components

Exergy Efficiency Analysis

The system's exergy details are presented in table 4.7. From the table, a notable variation in terms exergetic performance can be observed among the solar PV components. From the results, the battery emerges as the component with greatest exergy efficiency metric of 87.95% revealing that the battery is functioning optimally. The inverter and the solar charge display exergy efficiency of 86% and 84.22%, indicating that they are working efficiently. However, the solar panel exhibiting a substantially low exergy efficiency of 31.95% is an indication that optimization efforts should be directed towards it. These metrics had revealed that the solar panel is chief source of losses and its optimization can improve the overall operational efficiency of the system. These metrics are illustrated in figure 4.7 shown below.

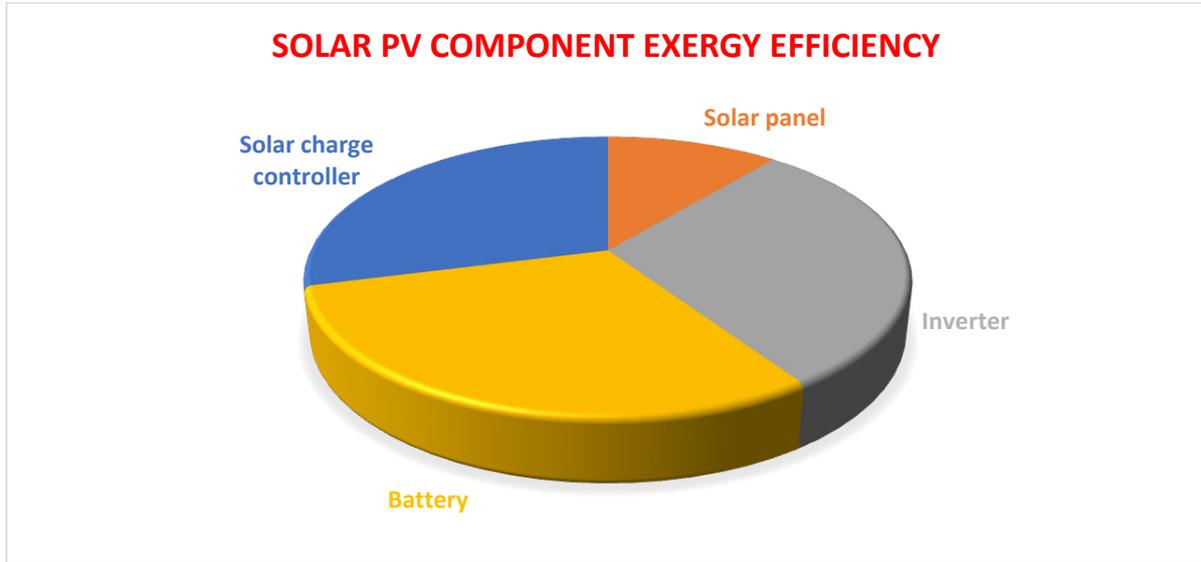| SOLAR PV COMPONENTS	EXERGY EFFICIENCY [EX_{EFF}][%]
Solar panel	31.95
Inverter	86.00
Battery	87.95
Solar charge controller	84.22

Table 4.7: Exergy Efficiency

Figure 4.7: Solar PV Component Exergy Efficiency Pie Chart

Exergy Improvement Potential Analysis

The exergy improvement potential details of the system are presented in table 8. From the result it can be observed that the probability or opportunity for the system improvement potential is on the high side. The solar panel possessed an improvement potential of 732.19, representing 99.5% of the total improvement potential. This suggests that the solar panel can be optimized for substantial benefit and or gain. However, the inverter, battery, and solar charge controller have relatively low exergy improvement potentials of 1.29, 1.03, and 1.31, respectively, portraying a relatively low improvement potential in these components. Figure 4.8. presents the visual representation

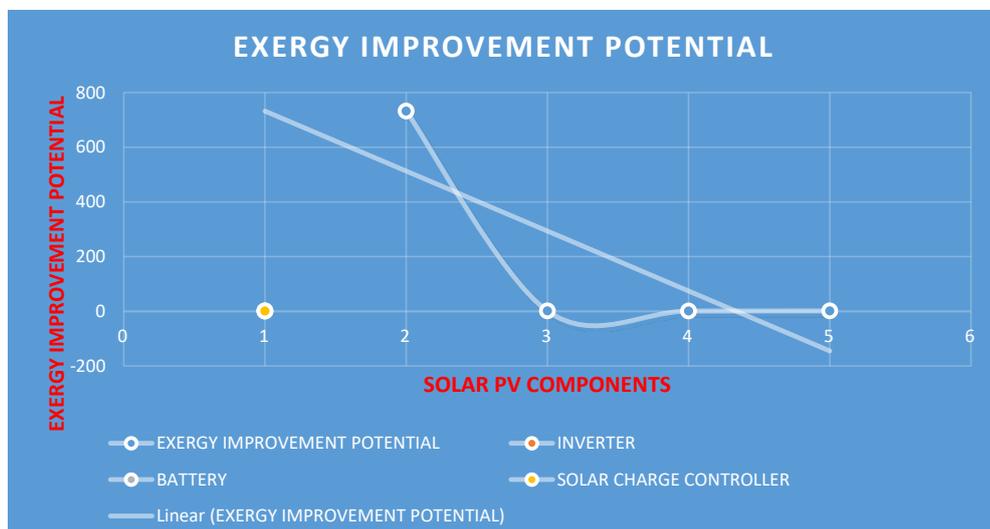| SOLAR PV COMPONENTS	EXERGY IMPROVEMENT POTENTIAL
Solar panel	732.19
Inverter	1.29
Battery	1.03
Solar charge controller	1.31

Table 4.8: Exergy Improvement Potential

Figure 4.8: Exergy Improvement Potential

Exergy Sustainability Index Analysis

Table 4.9. presents the exergy sustainability index details. The Exergy Sustainability Index (ESI) is a metric that evaluates a system's ability to utilize exergy sustainably, with higher values indicating better sustainability. The solar PV components' ESI values reveal significant variations, with the battery having the highest value at 58.32, indicating excellent sustainability and contributing approximately 67.9% to overall sustainability. The solar charge controller and inverter display modest ESI values of 14.253 and 12.09, which approximately represents metrics of 16.6% and 14.1%, respectively. However, the solar panel shows a comparatively low ESI value of 1.35, amounting to only about 1.6% of the total sustainability indices. This implies that, it necessitates substantial improvement to augment system sustainability. Noteworthy, the battery emerged as the most sustainable component of the system. Finally, to improve the system performance, the sustainability index of the solar panel should be increased. The visual representation of the sustainability index is presented in figure 4.9 shown below.

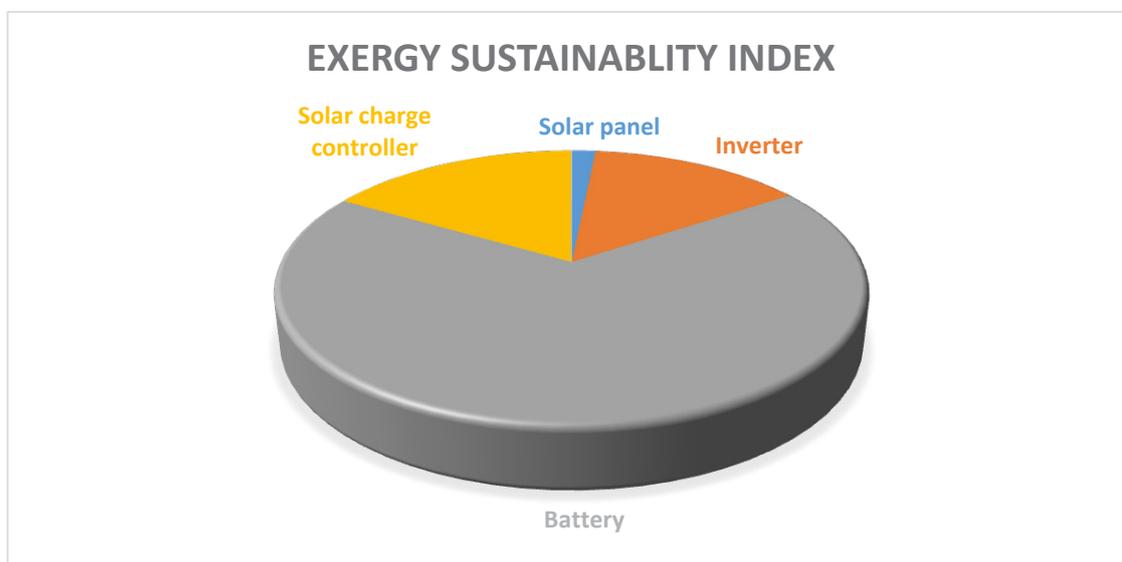| SOLAR PV COMPONENTS	EXERGY SUSTAINABLITY INDEX
Solar panel	1.35
Inverter	12.09
Battery	58.32
Solar charge controller	14.253

Table 4.9: Exergy Sustainability Index

Figure 4.9: Exergy Sustainability Index of Solar PV Components

Conclusion

In conclusion, the comprehensive exergy analysis of the solar PV system reveals significant opportunities for improvement. The solar panel is identified as the primary source of exergy losses, accounting for 10.1% of total exergy loss, but displays 26.92% energy efficiency, 31.95% exergy efficiency, 68.89% exergy destruction, 99.5% exergy destruction ratio, and a significant level of exergy improvement potential. The battery, inverter, and solar charge controller demonstrate relatively high efficiency and sustainability, with the battery contributing 67.9% to overall sustainability, followed by the solar charge controller (16.6%), inverter (14.1%), and solar panel (1.6%). The exergy efficiency of the components is 31.95% for the solar panel, 86.00% for the inverter, 87.95% for the battery, and 84.22% for the solar charge controller. To enhance overall system performance and sustainability, optimization efforts should focus on improving the solar panel's design, material, or operating conditions, which accounts for the majority of exergy destruction and improvement potential. By addressing these inefficiencies, the solar PV system can maximize its potential, reduce losses, and contribute to a more sustainable energy future [16].

Declaration

I wish to declare that the concepts, development, writing and other aspects of this research are the complete work of the author who only sparingly use AI technology to enhance the grammatical integrity of the write up.

Statement of data availability: All data employed in the analysis in addition to the ones that corroborated the research findings are included in the article. Upon request, the data can be made available.

Authors contributions: This work is the single contribution of the author

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