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Energy Interaction and Optimisation Within a Solar Panel Collector at Peak Hours of Irradiation

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Abstract - Nigeria, like many developing nations, faces challenges in providing reliable and affordable electricity, the country relies heavily on fossil fuels such as petroleum and natural gas to power its electrical grid in order to meet the high energy demand solar energy have been developed. It offers numerous advantages as compared to other forms of energy like fossil fuels and other deposits. A PV solar panel is a grouping of small solar cells. These cells are organized in a specific arrangement to provide a large amount of electricity. One of the approaches to benefit from the sun energy and convert it to thermal and electrical energy is through photovoltaic (PV) Panels, the amount of energy that can be converted by a solar cell is determined by the effective insolation time, the type of PVpanel used and also the critical wether conditions lijke the humidity, Temperature, Wind etc.. This study focuses on the Energy interaction within a solar panel collector at peak hours of irradiation. Although the methods used in generation of electrical energy is same in every cell but the efficiency factor depends upon the type of material that is being used in a cell. Each kind of material used in a cell has its own advantages and disadvantages. Solar panel designs consist four main components: solar panels, an inverter, an AC breaker panel, and a net meter. Some of the common features of the solar panel is to determine the amount of electricity that a solar panel can produce, the dimensions of the solar panel and how much space it occupies, the ability of the solar panel to withstand harsh weather conditions and physical damage. To determine the ratio of the electricity output to the solar input of the solar panel (efficiency) $P_{PV} = \frac{P_{load}}{PSH.\eta_{system}}$***, and lastly the guarantee of the solar panel manufacturers or installer to repair or replace defective panels. A comprehensive literature review was conducted on solar panel, solar declination,*** $\delta = 23,45^0 \sin(360^0 \frac{284+n}{365})$***, tilt angle, and solar angles to determine the enhance the solar irradiance factor at peak sun hour.***

Key Words: Potrntial, Factors, Based, Efficiency, Forces, Systems

I. INTRODUCTION

Nigeria is the most populous country and the largest economy in the African continent; but its power sector is currently underdeveloped. Remarkably, its economic and energy security depend on dwindling fossil fuel reserves. The country relies heavily on fossil fuels such as petroleum and natural gas to power its electrical grid (Ajayi, 2019). Yet, the Nigerian landscape experiences an average daily solar intensity of 20.1 MJ/m^2/day; and the wind speed across the states ranges from 1.5 to 4.1 ms^{-1}; with potential for harnessing energy from biomass, geothermal and water.

Future energy supply needs to satisfy factors such as sustainability, economy, efficiency and low environmental impact in order to reduce global energy crises, climate change and energy poverty, simultaneously. Presently, the efficiency of some of the renewable energy technologies (RETs) are yet to be optimised; but, demand for renewable energy (RE) sources has continued to increase globally because of its clean, sustainable, futuristic, environmentally benign and inexhaustible nature. Focus on RETs by governments, industrialists and users means that the advancements of functional materials, technologies for harvesting, converting, storing and conserving energy from renewable sources would continue to increase. Also, the attention on low carbon development would subsist as long as the emissions of greenhouse gases (GHG), which cause anthropogenic interferences on the climate system continue. Alternatives to fossil fuels that can utilize Nigeria's abundant solar resources are increasingly seen as promising solutions. Solar energy offers a renewable, indigenous source of power that could enhance energy security and sustainability if managed properly.

One of the approaches to benefit from the sun energy and convert it to thermal and electrical energy is through photovoltaic (PV) Panels, the amount of energy that can be converted by a solar cell is determined by the effective insolation time. The energy interactions within a solar panel collector at Peak sun hours (PSH) are the focus of this research.

The currently available PV technologies possess less than 23% conversion efficiencies, which underlines the need for further improvements to ensure better competitiveness (Alami et al., 2022). Heat management methods and cooling techniques can play a vital role in enhancing the performance of PV systems. Researchers, worldwide developed approaches to cool PV modules and conducted experimental and simulation studies to estimate their potential in improving the PV conversion efficiencies such as (Hasanuzzaman et al., 2016) and (Reddy et al., 2015).

At peak irradiation, solar panels may experience temperature rises that affect their efficiency, as higher temperatures can decrease the electrical output. Energy loss due to reflection, transmission, and internal resistive heating may further impact overall performance. Understanding the precise energy flow, temperature variations, and efficiency dynamics during peak solar irradiation is essential for optimizing the design, materials, and placement of solar panels, ultimately improving energy capture and conversion rates. This research is to provide a comprehensive assessment of the energy exchange and interactions within the solar PV panel collectors which determines the performance or the resultant output of the system. Amount of energy to be realised also reports the latest technical advancements related to soiling mitigation and heat management approaches to improve the performance of solar PV systems. This will enhance the performance of solar energy systems during the most critical periods of solar power generation, contributing to more effective and sustainable energy solutions. Focusing on the following objectives:

- Measuring the intensity and variability of solar irradiation during peak hours (10:00 AM - 4:00 PM) at the location of interest. Identify fluctuations in irradiation and their effects on solar panel performance over time.
- Evaluating the conversion efficiency of solar panels at peak irradiation, focusing on the relationship between incident sunlight and electrical output.
- Analysing Thermal Effects on peak hours of solar irradiation
- Assessing Energy Losses during the peak hour of irradiation
- Evaluating Panel Design and Cooling Mechanisms:
- Developing Optimization Strategies
- Modelling Energy Flow and Performance

By achieving these objectives, the study will contribute to enhancing solar panel system performance, ensuring that solar energy is captured more effectively during peak irradiation hours, and advancing the potential for more efficient and sustainable solar power systems.

2.1 Conceptual review

In 1839, Alexandre Edmond Becquerel a French physicist observed the ability of some materials to create an electrical charge from light exposure. It is a photovoltaic system that uses solar energy to produce electricity. Solar panels are made up of solar cells, which absorb sunlight. They use this sunlight to create direct current (DC) electricity through a process called "the photovoltaic effect." Because most appliances don't use DC electricity, devices called inverters then convert it to alternating current (AC) electricity, the form that is used in the homes. Most common solar panel sizes include *100-watt*, *300-watt*, and *400-watt* solar panels. The biggest the rated wattage of a solar panel, the more kWh per day it will produce. At peak hours of irradiation, a 300-watt solar panel will produce anywhere from 0.90 to 1.35 kWh per day (at 4-6 peak sun hour's locations). A 400-watt solar panel will produce anywhere from 1.20 to 1.80 kWh per day (at 4-6 peak sun hours locations). The biggest 700-watt solar panel will produce anywhere from 2.10 to 3.15 kWh per day (at 4-6 peak sun hours locations).

Solar panel designs consist four main components: solar panels, an inverter, an AC breaker panel, and a net meter. Some of the common features of the solar panel is to determine the amount of electricity that a solar panel can produce, the dimensions of the solar panel and how much space it occupies, the ability of the solar panel to withstand harsh weather conditions and physical damage. To determine the ratio of the electricity output to the solar input of the solar panel (efficiency), and lastly the guarantee of the solar panel manufacturers or installer to repair or replace defective panels. Alexandre Edmond Becquerel in 1839 observed the photovoltaic (PV) effect via an electrode in a conductive solution exposed to light a process that produces a voltage or electric current when exposed to light or radiant energy. A few decades later, French mathematician Augustin Mouchot was inspired by the physicist's work. He began registering patents for solar-powered engines in the 1860s. From France to the U.S, inventors were inspired by the patents of the mathematician and filed for patents on solar-powered devices as early as 1888. In 1883 when New York inventor Charles Fritts created the first solar cell by coating selenium with a thin layer of gold. Fritts reported that the selenium module produced a current "that is continuous, constant, and of considerable force." This cell achieved an energy conversion rate of 1 to 2 percent. Most modern solar cells work at an efficiency of 15 to 20 percent. So, Fritts created what was a low impact solar cell, but still, it was the beginning of photovoltaic solar panel innovation in America. Named after Italian physicist, chemist and pioneer of electricity and power, Alessandro Volta, photovoltaic is the more technical term for turning light energy into electricity, and used interchangeably with the term photoelectric.

Only a few years later in 1888, inventor Edward Weston received two patents for solar cells -U.S. Patent 389,124 and U.S. Patent 389,425. For both patents, Weston proposed, "to transform radiant energy derived from the sun into electrical energy, or through electrical energy into mechanical energy." Light energy is focused via a lens (f) onto the solar cell (a), "a thermopile (an electronic device that converts thermal energy into electrical energy) composed of bars of dissimilar metals." The light heats up the solar cell and causes electrons to be released and current to flow. In this instance, light creates heat, which creates electricity; this is the exact reverse of the way an incandescent light bulb works, converting electricity to heat that then generates light.

That same year, a Russian scientist by the name of Alexander Grigorievich Stoletov created the first solar cell based on the photoelectric effect, which is when light falls on a material and electrons are released. This effect was first observed by a German physicist, Heinrich Hertz. In his research, Hertz discovered that more power was created by ultraviolet light than visible light. Today, solar cells use the photoelectric effect to convert sunlight into power.

In 1894, American inventor Melvin Severy received patents 527,377 for an "Apparatus for mounting and operating thermopiles" and 527,379 for an "Apparatus for generating electricity by solar heat." Both patents were essentially early solar cells based on the discovery of the photoelectric effect. The first generated "electricity by the action of solar heat upon a thermo-pile" and could produce a constant electric current during the daily and annual movements of the sun, which alleviated anyone from having to move the thermopile according to the sun's movements. Severy's second patent from 1889 was also meant for using the sun's thermal energy to produce electricity for heat, light and power. The "thermos piles," or solar cells as we call them today, were mounted on a standard to allow them to be controlled in the vertical direction as well as on a turntable, which enabled them to move in a horizontal plane. "By the combination of these two movements, the face of the pile can be maintained opposite the sun all times of the day and all seasons of the year," reads the patent.

Almost a decade later, American inventor Harry Reagan received patents for thermal batteries, which are structures used to store and release thermal energy. The thermal battery was invented to collect and store heat by having a large mass that can heat up and release energy. It does not store electricity but "heat," however, systems today use this technology to generate electricity by conventional turbines. In 1897, Reagan was granted U.S. patent 588,177 for an "application of solar heat to thermo batteries." In the claims of the patent, Reagan said his invention included "a novel construction of apparatus in which the sun's rays are utilized for heating thermo-batteries, the object being to concentrate the sun's rays to a focus and have one set of junctions of a thermo-battery at the focus of the rays, while suitable cooling devices are applied to the other junctions of said thermo-battery." His invention was a means to collecting, storing and distributing solar heat as needed.

In 1913, William Coblentz, of Washington, D.C., received patent 1,077,219 for a "thermal generator," which was a device that used light rays "to generate an electric current of such a capacity to do useful work." He also meant for the invention to have cheap and strong construction. Although this patent was not for a solar panel, these thermal generators were invented to either convert heat directly into electricity or to transform that energy into power for heating and cooling.

By the 1950s, Bell Laboratories realized that semiconducting materials such as silicon were more efficient than selenium. They managed to create a

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solar cell that was 6 percent efficient. Inventors Daryl Chapin, Calvin Fuller, and Gerald Pearson (inducted to the National inventors Hall of Fame in 2008) were the brains behind the silicon solar cell at Bell Labs. While it was considered the first practical device for converting solar energy to electricity, it was still cost prohibitive for most people. Silicon solar cells are expensive to produce, and when you combine multiple cells to create a solar panel, it's even more expensive for the public to purchase. University of Delaware is credited with creating one of the first solar buildings, ‘‘Solar One’’ in 1973. The construction ran on a combination of solar thermal and solar photovoltaic power. The building didn’t use solar panels; instead, solar was integrated into the rooftop.

It was around this time in the 1970s that an energy crisis emerged in the United States. Congress passed the Solar Energy Research, Development and Demonstration Act of 1974, and the federal government was committed more than ever ‘‘to make solar viable and affordable and market it to the public” After the debut of “Solar One,” people saw solar energy as an option for their homes. Growth slowed in the 1980s due to the drop in traditional energy prices. But in the next decades, the federal government was more involved with solar energy research and development, creating grants and tax incentives for those who used solar systems. According to Solar Energy Industries Association, solar has had an average annual growth rate of 50 percent in the last 10 years in the United States, largely due to the Solar Investment Tax Credit enacted in 2006. Installing solar is also more affordable now due to installation costs dropping over 70 percent in the last decade.

Recently, Solar Engineering, Enpulz, Guardian Industries Corporation, Solar City Corporation, United Solar Systems, and Tesla (after their merger with Solar City have all been issued patents for solar cells that are much more discreet than the traditional solar panel. All of the patents incorporate photovoltaic systems, which transform light into electricity using semiconducting materials such as silicon.

2.2 Types of Solar Panel

There are three main types of solar panels used in solar projects namely

- Monocrystalline

Monocrystalline solar panels are highly efficient and have a sleek design, but come at a higher price than other solar panels. They are the most popular solar panels used in rooftop solar panel installations today. Monocrystalline silicon solar cells are manufactured using something called the Czochralski method, in which a ‘seed’ crystal of silicon is placed into a molten vat of pure silicon at a high temperature. This process forms a single silicon crystal, called an ingot, which is sliced into thin silicon wafers which are then used in the solar modules. Monocrystalline solar panel has the highest performance. The Efficiency ratings of monocrystalline solar panels range from 17% to 22%, earning them the title of the most efficient solar panel type. The higher efficiency rating of monocrystalline panels makes them ideal for homes with limited roof space, as you’ll need fewer panels to generate the electricity you need. Monocrystalline solar panels have their manufacturing process to thank for being so efficient. Because monocrystalline solar cells are made of a single crystal of silicon, electrons are able to easily flow throughout the cell, increasing overall efficiency. Not only do monocrystalline panels have the highest efficiency ratings, they typically also have the highest power capacity ratings, as well. Most monocrystalline panels on the market today will have a power output rating of at least 320 watts, but can go up to around 375 watts or higher. Monocrystalline panels are the most expensive of the three types of solar panels because of their manufacturing process and higher performance abilities.

However, as manufacturing processes and solar panel technology in general has improved, the price difference between monocrystalline and polycrystalline panels has shrunk considerably. According to the Lawrence Berkeley National Laboratory, monocrystalline solar panels now sell for just about $0.05 per watt higher than polycrystalline modules. Monocrystalline panels have a solid black appearance, making them pretty subtle on your roof. But, the way monocrystalline solar cells are shaped causes there to be quite a bit of white space on the panel. Some manufacturers have worked around this with black packing or shaping the cells differently, but these aesthetic changes can impact both the price and performance of the panels. Overall, monocrystalline panels still look sleek, but they’re a bit more pronounced than thin film panels.

- Polycrystalline

Polycrystalline panels, sometimes referred to as 'multicrystalline panels', are popular among homeowners looking to install solar panels on a lower budget. They are cheaper than monocrystalline panels, however, they are less efficient and aren't as aesthetically pleasing.

Similar to monocrystalline panels, polycrystalline panels are made of silicon solar cells. However, the cooling process is different, which causes multiple crystals to form, as opposed to one. Polycrystalline panels used on residential homes usually contain 60 solar cells.

Polycrystalline solar panels has the mid-tier performance amongst the three types of solar panels. Polycrystalline panel efficiency ratings will typically range from 15% to 17%. The lower efficiency ratings are due to how electrons move through the solar cell. Because polycrystalline cells contain multiple silicon cells, the electrons cannot move as easily and as a result, decrease the efficiency of the panel.

The lower efficiency of polycrystalline panels also means they tend to have a lower power output than monocrystalline panels, usually ranging between 240 watts and 300 watts. 300 watts solar panels aren't seen as often in residential applications, but some polycrystalline panels have power ratings above 300 watts. However, new technologies and manufacturing processes have given the efficiency and power ratings of polycrystalline panels a slight boost over the years, slowly closing the performance gap between mono and polycrystalline panels. Polycrystalline panels have been the cheapest option for homeowners going solar, without majorly sacrificing panel performance. Low prices allowed polycrystalline panels to make up a significant market share in residential solar installations between 2012 and 2016.

But as we said earlier, the price gap between monocrystalline and polycrystalline panels is narrowing. Now, more homeowners are willing to pay a slightly higher price to get significantly better efficiency and power ratings from monocrystalline panels. Polycrystalline panels tend to stick out like a sore thumb. The process in which polycrystalline solar cells are manufactured causes the cells to have a blue, marbled look. This means each individual polycrystalline panel looks substantially different from the one next to it. Most homeowners aren't too keen on the aesthetics of polycrystalline panels.

- Thin-film.

Thin film solar panels are the cheapest, but have the lowest efficiency rating and require a lot of space to meet your energy needs. Thin film solar cells are mostly used in large-scale industrial and utility solar installations because of their lower efficiency ratings. Thin film solar panels are made by depositing a thin layer of a photovoltaic substance onto a solid surface, like glass. Some of these photovoltaic substances include amorphous silicon (a-Si), copper indium gallium selenide (CIGS), and cadmium telluride (CdTe). Each of these materials creates a different 'type' of solar panel, however, they all fall under the thin film solar cell umbrella. During the manufacturing process, the photovoltaic substance forms a thin lightweight sheet that is, in some cases, flexible. Thin-film solar panels have incredibly low efficiency ratings. As recently as a few years ago, thin-film efficiencies were in the single digits. Researchers have recently achieved 23.4% efficiency with thin film cell prototypes but thin-film panels that are commercially available generally have efficiency in the 10 –13% range.

In order to meet your energy needs, you would need to install more thin-film panels over a large area to produce the same amount of electricity as crystalline silicon solar panels. This is why thin-film solar panels don't really make sense for residential installations where space is limited.

Thin film solar panels have the lowest cost of the solar panel types, largely because they are easier to install and require less equipment. However, they also have *much lower* performance abilities and require a substantial amount of space to generate enough electricity to power a home. Plus, thin film panels degrade much faster than other panel types, meaning they need to be replaced more often, which leads to more long-term recurring costs.

Thin film panels have a clean, all-black look. Their thin design allows them to lie flat against roofs, so they are able to blend in more seamlessly. In fact, with some thin film panels, it's hard to even see the individual cells within the panel. They also tend to have less wiring and busbars, meaning there's less white space. However, because they are so inefficient, you would need to cover your *entire* *roof* in thin film panels - which may or may not be your style.

Concussively Monocrystalline solar panels are the best solar panel type for residential solar installations. Although you will be paying a slightly higher price, you'll get a system with a subtle appearance without having to sacrifice performance or durability. Plus, the high efficiency and power output ratings you get with monocrystalline panels can provide you with better savings over the lifetime of your system. If you're on a tight budget, polycrystalline panels might make more sense for you. Thin film solar panels are not recommended for residential installations - their performance and durability don't make the low cost worth it, and it's unlikely you'll have nearly enough space to install the number of thin film panels you would need to cover your household electricity usage.

- Passivated Emitter and Rear Contact cells (PERC) solar panels

Passivated Emitter and Rear Contact cells (PERC) solar panels also known as 'rear cells', PERC solar panels are manufactured using advanced technology. It is done by adding a layer on the back of solar cells. The traditional solar panels absorb sunlight only to some extent and some light passes straight through them. The additional layer in the PERC panels allows this unabsorbed sunlight to be absorbed again from the rear side of the panels, making it even more efficient. Nowadays, PERC technology is typically combined with Monocrystalline cells to produce high efficiency Mono-PERC panels which have the highest power ratings among commercially available solar panels.

2.3 Features of Passivated Emitter and Rear Cell (PERC) solar panels

1. PERC solar panels are more efficient as compared to traditional solar panels as they absorb more sunlight.
2. There is an additional layer at the back of the panels which reflects the unabsorbed sunlight back to the solar cells for further absorption of the sunlight.

- Bifacial solar panels

Bifacial solar panels generate solar power from both direct sunlight *and* reflected light (albedo), which means they are essentially double-sided panels. That's a big difference from the more common monofacial solar panels, which generate power only from the sun-facing side. Bifacial solar was produced by Bell Laboratories in 1954. However, despite their potential for increased efficiency, bifacial solar panels do not have the widespread adoption of monofacial solar panels, due in part to their relative cost as well as the more specific environmental conditions they require. By capturing albedo as well as direct sunlight, the amount of electricity generated by each bifacial panel increases, meaning fewer solar panels need to be installed. Unlike monofacial solar panels, they are made of transparent glass, which lets some of the light pass through and reflect off of the surface below. To further increase the amount of light passing through, they use glass instead of metal frames or grid lines to hold them in place. The glass is tempered glass reduce scratching. Otherwise, they perform exactly as other photovoltaic (PV) panels work, using crystalline silicon to absorb sunlight and convert it into an electric current. The backside of a bifacial solar panel usually shares its circuitry with the front side, thus increasing the efficiency without increasing the circuitry. Bifacial panels can generate up to 9% more electricity than monofacial panels, according to recent research by the National Renewable Energy Laboratory (NREL), a division of the U.S. Department of Energy. As is the case with higher efficiency monofacial panels, this means that fewer panels need to be installed as well as the associated hardware like panel mounts, inverters, and cables reducing both hardware costs and labor costs. Solar PV technology is less efficient at higher temperatures, which gives bifacial panels another advantage. Because they are made of glass without the heat-absorbing aluminum backing of monofacial panels, they have lower working temperatures, which adds to their efficiency. Bifacial panels don't need to be grounded, since they lack metal frames that might potentially conduct electricity. And since their construction makes them more durable, they often come with longer warranties 30 rather than 5 year for mono-facial panels. Because bifacial panels rely more on diffuse solar radiation, they are more efficient than mono-facial panels in cloudy climates, or anywhere there is less direct sunlight and a greater percentage indirect, diffuse insolation. For the same reason, bifacial panels are more efficient for longer periods of the day, when there is still diffuse sunlight but none directly shining on the panels. Bifacial panels can also better benefit from solar trackers to follow the sun throughout the day. With tracking, the electricity generated has been shown by one study to increase by 27% over mono-facial panels, and by 45% over fixed-tilt bifacial panels.

Another study with similar results determined that bifacial panels on solar trackers decreased the cost of electricity by 16%.

Below is a selected, streamlined, and well-arranged version of your material, rewritten to directly align with the topic:

2.4 Applications of Solar Cells

Solar cells convert incident solar radiation into electrical energy through the photovoltaic effect. Their applications demonstrate the practical importance of optimizing energy capture, especially during peak irradiation periods.

Residential and Commercial Buildings: Rooftop photovoltaic (PV) systems supply electricity by harvesting solar energy during peak sun hours, improving energy efficiency and reducing grid dependence.

Solar Water Pumping Systems: Widely used in agriculture, these systems rely heavily on high irradiance periods to ensure adequate power generation and water flow.

Street Lighting Systems: Solar-powered streetlights store energy harvested during peak irradiation hours and utilize it during night time operation.

Solar-Powered Vehicles: Solar panels integrated into vehicles convert high-intensity sunlight into electrical energy, stored in batteries for extended use. Advances in materials such as carbon nanotubes enhance light absorption and conversion efficiency (Askari Mohammad Bagher et al., 2015).

These applications emphasize the need for efficient energy interaction and optimization during peak solar irradiation.

2.5 Peak Hours of Irradiation

Peak Sun Hours (PSH) represent the period during which solar irradiance averages 1 kW/m², indicating maximum potential energy availability for photovoltaic conversion.

2.5.1 Effect of Peak Sun Hours on Energy Productivity

Peak sun hours significantly influence the energy output of a solar panel collector. During PSH, solar panels receive maximum solar radiation, leading to optimal photovoltaic energy conversion. Knowledge of PSH enables:

1. Optimization of panel tilt angle, orientation, and positioning
2. Improved energy storage and load management
3. Accurate forecasting of photovoltaic system performance

The effective insolation time, rather than total daylight duration, determines the actual energy yield of a PV system. Maximum energy conversion occurs during average peak irradiation periods.

PSH is mathematically defined as the ratio of daily solar radiation received to the standard irradiance of 1,000 W/m². Typical PSH values range between 3–7 hours per day, depending on geographical location and atmospheric conditions.

2.5.2 Peak Sun Hours in Nigeria (Optimization Perspective)

Nigeria possesses strong solar energy potential due to its geographical location.

Northern Nigeria: 6–7 PSH/day, Central and Eastern Nigeria: 5–6 PSH/day, Western Nigeria: 4–6 PSH/day, and Southern Nigeria: 4–5 PSH/day.

These variations highlight the importance of location-specific optimisation of solar panel collectors. Accurate PSH assessment supports proper sizing, configuration, and expected energy yield of photovoltaic systems, particularly in states such as Anambra.

2.6 Energy Interactions within the Solar Panel Collector

Energy interaction in a solar panel collector begins when solar radiation strikes the photovoltaic surface, initiating electron excitation and charge transport processes that result in electrical energy generation.

2.6.1 Photovoltaic Energy Conversion

Photovoltaic conversion is the direct transformation of solar radiation into electricity without intermediate thermal processes. PV systems are solid-state devices characterized by durability, low maintenance, and scalability from microwatt to megawatt applications. Advancements in materials and manufacturing have significantly improved PV efficiency, reduced energy payback periods to 2–5 years, and extended panel lifetimes beyond 30 years.

2.6.2 Semiconductor Interaction Mechanism

Silicon-based semiconductors dominate PV technology due to their suitable band gap and availability.

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Key interaction processes include:, Generation of electron–hole pairs upon photon absorption, Separation of charge carriers via the internal electric field, Charge collection at electrodes, producing usable electrical power, and Doping silicon with phosphorus (n-type) or boron (p-type) forms a p–n junction, which establishes an internal electric field essential for directing charge flow and minimizing recombination losses.

2.6.3 Photovoltaic (PV) Effect and Energy Optimization

When photon energy equals or exceeds the semiconductor band gap, electrons transition from the valence band to the conduction band, enabling electrical conduction. Photons with energy below the band gap contribute only to heat generation, reducing conversion efficiency.

The p–n junction ensures that free electrons are directed through an external circuit, allowing useful power extraction before recombination occurs. Energy losses due to recombination and excess photon energy limit theoretical efficiency.

The Shockley–Queisser limit defines the maximum achievable efficiency of a single-junction solar cell as 33.7% under standard conditions (AM1.5 spectrum, 25°C), highlighting the importance of material selection and collector optimization.

III. METHODOLOGY

This study adopts a combined analytical, experimental, and statistical approach to evaluate and optimize the energy productivity of solar photovoltaic (PV) systems during peak sun hours. The methodology is structured into model development, optimization, and validation stages.

Model development begins with solar resource modeling, incorporating irradiance, temperature, and sun-path geometry. The photoelectric effect governing photovoltaic energy conversion is analytically described using fundamental semiconductor and radiation principles. Key solar geometry parameters including solar declination, hour angle, altitude, azimuth, and zenith angles are derived using standard astronomical relations to accurately characterize solar position and available irradiance throughout the year. Sun path diagrams are employed to assess shading effects and optimize panel orientation.

The tilt angle model is developed based on latitude dependent solar exposure to maximize incident radiation. Seasonal and regional tilt angle adjustments are considered, with specific emphasis on locations in Nigeria, particularly Anambra State, where optimal tilt angles are determined using latitude based empirical relations.

The optimization model focuses on enhancing PV performance during peak irradiation hours by minimizing thermal and conversion losses. Key performance indicators include irradiance utilization, conversion efficiency, and capacity factor. The study evaluates the influence of temperature variation, solar intensity, and cooling strategies (such as natural and forced convection) on PV output. The thermal behaviour of PV modules is analysed using diode based electrical models, highlighting the inverse relationship between operating temperature and efficiency.

Experimental validation involves both indoor and outdoor testing of multi-crystalline silicon PV modules under standard test conditions and real outdoor composite climatic conditions. Indoor testing is conducted using a calibrated solar simulator, while outdoor measurements are performed under high-irradiance environments using controlled mounting and instrumentation to reduce thermal interference.

To quantify the impact of climatic variables, regression and correlation analyses are applied using long-term experimental data. Ambient temperature and solar irradiance are treated as independent variables, while module efficiency is the dependent variable. Both multiple linear regression and polynomial regression models are developed to capture nonlinear performance trends. Model adequacy is assessed through residual analysis and comparison of predicted and experimental efficiency values.

Overall, the methodology provides a systematic framework for analyzing, optimizing, and validating PV system performance under peak solar irradiation conditions, with strong relevance to hot and composite climate regions.

II. RESULTS AND DISCUSSION

To study the effect of the three selected parameter conditions of the PV Module performance, a full quadratic model for each response was selected based on the best fit of the experimental data. Thus, a statistical significance of the developed models was evaluated using an analysis of variance (ANOVA) and the accuracy of the models was further justified through a regression analysis, and normal plot of residuals. The experimental results obtained at different combinations of processing conditions are presented in Table 4.1.

Data Point j	Dependent Variable (Efficiency) Y*	Independent Variable (Ambient Temperature) X_1	Independent Variable (Radiation) X_2
1	9.53	22.00	535
2	11.79	25.00	801
3	12.18	34.00	881
4	11.36	40.25	892
5	11.00	49.44	978
6	11.12	40.36	895
7	11.16	40.47	910
8	11.66	43.76	910
9	11.83	35.65	954
10	10.36	39.00	697
11	9.83	26.80	600
12	8.90	21.00	473

Table 4.1 Regression Input

Observation	Predicted Y	Residuals	Standard Residuals
1	9.656864	-0.12686	-0.38008
2	11.53735	0.252645	0.756919
3	11.581	0.598999	1.794586
4	11.26394	0.096063	0.287801
5	11.34212	-0.34212	-1.02497
6	11.28024	-0.16024	-0.48007
7	11.39009	-0.23009	-0.68935
8	11.52109	0.138911	0.416174
9	12.23091	-0.40091	-1.20111
10	9.824201	0.535799	1.60524
11	9.854262	-0.02426	-0.07269
12	9.237938	-0.33794	-1.01245

Table 4.2 Residual Output

4.1 Analysis of Variance (ANOVA)

Analysis of variance (ANOVA) comprises a set of statistical models and related estimation techniques. It's used to examine variations both within and between groups, especially when analysing differences in group means within a sample. ANOVA was employed in this study to determine if there's a noteworthy difference in the experiment's mean values. Tables 4.1, and 4.2 showcase the outcomes of ANOVA concerning the Residual Input and the Residual Output, derived from the experimental data. These tables detail the statistical significance of the factors under consideration and also provide information about the coefficients of the respective models.

There are two tables in ANOVA (Analysis of variance)

Table 4.3 ANOVA output (part I)

ANOVA					
	df	*SS*	MS	F	Significance F
Regression	2	10.29796	5.148979	37.81353	4.17E-05
Residual	9	1.225509	0.136168		
Total	11	11.52347			

	Intercept	X Variable 1 (ambient temperature)	X Variable 2 (radiation)
Coefficients	6,903722	0.007796	-0.06445
Standard Error	0.509808	0.001095	0.021388
T Stat	13.5418	7.117329	-3.01346
P-value	2.73E-07	5.56E-05	0.014634
Lower 95%	5.750456	0.005318	-0.11283
Upper 95%	8.056988	0.010274	-0.01607

4.2 Predicted and Actual Results for the two (2) Responses:

Determination of the efficiency of PV module using Coefficients

Coefficients are listed in the second table of ANOVA table 4.3. These coefficients allow the program to calculate predicted values of the dependent variable Y (efficiency of PV module) which were used above in formula (21) and are a part of residual output Table 4.2

4.2.1 Sum of Squares

In the ANOVA regression output one will find three types of sum of squares (Table 4.1)

Total Sum of Squares

SS_T (Total sum of squares) = $SS_E + SS_R$ (22)

Where SS_E - residual (error) Sum of Squares , SS_R - regression sum of squares

It is obvious that SS_T is the sum of squares of deviations of the experimental values of dependent variable Y*(Efficiency of the PV module) from its average value. SST could be interpreted as the sum of deviations of Y* from the simplest possible model.

Residual (or error) sum of squares (SS_E)

SS_E could be viewed as the due –to – random-scattering of- Y- about – predicted –line contributor to the total sum of squares SS_T. This is the reason for calling the quantity "due to error (residual) sum of squares".

4.2.2 Regression Sum of Squares (SSR)

SS_R is the sum of squares of deviations of the predicted by-regression-model values of dependent variable (i.e. Efficiency of PV module) Y from its average experimental value Y^*_{avg}.. It accounts for addition of p(no.) variables (X_1, X_2,X_3,…..X_P) to the simplest possible model, here there is a transformation from the "non-regression model" to the true regression model, so SS_R is also called as " due to regression sum of squares".

Mean square (variance) and degrees of freedom

The general expression for the mean square of an arbitrary quantity q is

MSq = SSq / df (23)

SSq is the sum of squares and df is the number of degrees of freedom associated with quantity SSq. MS is also referred to as the variance. The number of degrees of freedom could be viewed as the difference between the number of observations n and the number of constraints (fixed parameters associated with the corresponding sum of squares).

Total mean square MST (total variance)

$MS_T = SS_T / (n-1)$ (24)

SST is associated with the model, which has only one constraint (parameter b_o), therefore the number of degrees of freedom in this case is:

$df_T = n-1$ (25)

Residual (error) mean square MS_E (error variance)

$MS_E = SS_E / (n-k)$ (26)

SS_E is associated with the random error around the regression model (1), which has k = p+1 parameters (one per each variable out of p variables total plus intercept). It means there are k constraints and the number of degrees of freedom is:

$df_E = n-k$ (27)

Regression mean square MS_R (regression variance)

$MS_R = SS_R / (k-1)$ (28)

The number of degrees of freedom in this case can be viewed as the difference between the total number of degrees of freedom (df_T = n-1) (25) and the number of degrees of freedom for residuals df_E (27).

$df_R = df_T – df_E = (n-1) – (n-k)$ (29)

$df_R = k-1= p$ (30)

4.2.3 Test of Significance and F- numbers

The F-number is the quantity which can be used to test for the statistical difference between two variances. For example, if we have two random variables R and E, the corresponding F-number is:

$F_R = MS_R/MS_E$ (31)

In our analysis F-number is 37.81353(F_R), the variances MS_R and MS_E are defined by an expression of type (23).

In order to tell whether two variances are statistically different, we determine the corresponding probability from F- distribution function:

$P = P (F_R, df_R, df_E)$ (32)

The quantities df_R, df_E – degrees of freedom for numerator and denominator- are parameters of this function.

The probability P given by (32) is a probability that the variances MS_R and MS_E are statistically indistinguishable. On the other hand, 1-P is the probability that they are different and is often called confidence level. Conventionally, a reasonable confidence level is 0.95 or higher. If it turns out that 1-P< 0.95, we say that MS_R and MS_E are statistically the same. If 1-P >0.95, we say that at least with the 0.95 (or 95%) confidence MS_R and MS_E are different. The higher the confidence level, the more reliable our conclusion, calculating the procedure numerically we get

Solving eqn (32)

$P= P (F_R, df_R, df_E)$ (32)

P= FDIST (37.81353, 2, 9) = 4.17157E-05 While calculating 1-P we get 1-P > 0.95 = 0.99995

Here the confidence level is much higher; signifying the conclusion to be more reliable. There are several F-tests related to regression analysis. Here three most common ones have been discussed. They deal with the significance of parameters in the regression model.

4.2.4 Significance test of all coefficients in the regression model

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This test is performed to check with what level of confidence we can state that AT LEAST ONE of the coefficients b (b_1, b_2…b_p) in the regression model is significantly different from zero.

After determining F_R i.e. F- number for the whole regression (part of regression output (as shown in table 4.3)).

The second step is to determine the numerical value of the corresponding probability PR (also a part of regression output)

Finally we can determine the confidence level 1-P (as calculated from equation 32). At this level of confidence, the variance "due to regression" MSR (5.148979) (from Table 4.3) is statistically different from the variance "due to error" MSE (0.136168) (from Table 4.3)). In its turn it means that the addition of p variables (X_1, X_2… X_p) to the simplest model where Y = b_o (dependent variable Y is just a constant) is a statistically significant improvement of the fit. Thus, at the confidence level not less than 1-P we can say: "At least ONE of the coefficients in the model is significant". The higher the FR the more accurate the corresponding model.

4.2.5 Significance test of subset of coefficients in the regression model

With what level of confidence can we be sure that at least ONE of the coefficients in a selected subset of all the coefficients is significant? So it is necessary to test a subset of the last m coefficients in the model with a total of p coefficients (b1, b2,….bp).

Here we need to consider two models:

$Y = bo + b_1X_1 + b_2X_2 + bp\ Xp$ (unrestricted) (33)

$Y = b'o + b'_1X_1 + b'_2X_2 + b'p\text{-}m\ Xp\text{-}m$ (restricted) (34)

These models are called unrestricted (33) and restricted (34) respectively. If we perform two separate least square regression analyses for each model. The regression output for the unrestricted model is already presented in Table 4.3. To test whether the quadratic terms are significant, in this case restricted model is considered where the equation comes out to be as

$Y = b_o + b_1X_1$ (restricted model) (35)

The subset of parameters consists of two parameters and m=2. By analogy with the input table for the unrestricted model (Table 4.1) we prepare for the restricted model:

Table 4.5 Regression input for restricted model (considering independent variable X_1= Ambient Temperature)

Data Point # j	Dependent Variable (Efficiency) Y*	Independent Variable (Ambient Temperature) X_1
1	9.53	22.00
2	11.79	25.00
3	12.18	34.00
4	11.36	40.25
5	11.00	49.44
6	11.12	40.36
7	11.16	40.47
8	11.66	43.76
9	11.83	35.65
10	10.36	39.00
11	9,83	26.80
12	8.90	21.00

We perform an additional regression using this input table and as part of ANOVA.

Table 4.6 Regression ANOVA output for the restricted model

ANOVA					
	df	ss	MS	F	Significance F
Regression	1	3.400	3.400	4.1857	0.067972
Residual	10	8.123	0.812		
Total	11	11.52			

From Table 4.3 and Table 4.5 we have:

SS_E = 1.225509 (Error sum of squares; unrestricted model)

MS_E = 0.136168 (Error mean square; unrestricted model)

df_E = n-k = 9 (Degrees of freedom; unrestricted model)

SS'E = 8.123266 (Error sum of squares; restricted model)

Now we are able to calculate $F_{m=2}$:

$F_{m=2}$= {(8.123266-1.225509)/2}/ 0.136168 = 25.328

Using the Microsoft Excel function for the F-distribution , we determine the probability $P_{m=2}$:

$P_{m=2}$ = FDIST (Fm=2, m, n-k), $P_{m=2}$ = FDIST (25.328, 2, 9) = 0.0002012

Finally we calculate the level of confidence

1- Pm=2 = 1-0.0002012 = 0.999798

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Here 1- P_m is big enough (greater than 0.95) we state that other coefficients in the subset are significant to a good extent.

Table 4.7 Regression input for restricted model (considering independent variable X_1= Radiation)

Data point # 1	Dependent Variable (Efficiency) Y*	Independent Variable (Radiation) X_1
1	11.70	535
2	11.68	801
3	11.67	881
4	11.39	892
5	10.83	978
6	10.45	895
7	10.50	910
8	10.54	954
9	10.69	978
10	11.31	697
11	11.57	600
12	11.64	473

We perform an additional regression using this input table and as part of ANOVA.

Table 4.8 Regression ANOVA output for the restricted model

	Regression	Residual (error)	Total
df'	1	10	11
SS'	9.0614	2.462	11.5234
MS'	9.0614	0.2462	
F'	36.8045		
Significance F'	0.000121		

From Table 4.3 and Table 4.7 we have:

SS_E = 1.225509

(Error sum of squares; unrestricted model)

MS_E = 0.136168 (Error mean square; unrestricted model)

df_E = n-k = 9

(Degrees of freedom; unrestricted model)

SS'_E = 2.4620

(Error sum of squares; restricted model)

Now we are able to calculate $F_{=2}$:

$F_{m=2}$ = 2.4620-1.225509)/2}/ 0.136168 = 4.5403

Using the Microsoft Excel function for the F-distribution we determine the probability $P_{m=2}$:

$P_{m=2}$ = FDIST ($F_{m=2}$, m, n-k)

$P_{m=2}$ = FDIST (4.5403, 2, 9) = 0.043314

Finally we calculate the level of confidence

1-Pm=2 = 1-0.043314 = 0.956687

Here 1-Pm is also big enough (greater than 0.95), we state that other coefficient in the subset is significant also to a good extent.

Significance test of an individual coefficient in the regression model

In our illustration P_0 = 2.73E-07, and P_2 = 0.014634, Table 6a corresponds to fairly high confidence levels, 1-P0 = 0.99999 and 1-P2=0.98536. This suggests that parameters b_o and b_2 are significant. The confidence levels for b_1 (1 P1=1- 5.56E-05) = 0.99994 are high, which means that it is significant.

4,2.6 Confidence Interval

For the unrestricted model, the lower and upper 95% limits for intercept are "5.75045"and "8.05698" respectively. The fact that with the 95% probability zero does not fall in this interval is consistent with our conclusion of significance of b_0 made in the course of F-testing of individual parameters. The confidence levels at the 95% for b_1 do not include zero. This also agrees with the F-Test of individual parameters.

Regression Statistics Output

Table 4.9 Regression Statistics Output

Multiple R	0.945331
R Square (R^2)	0.893651
Adjusted R^2(R^2 $_{adj}$)	0.870018
Standard Error (S_y)	0.369009
Observations (n)	12

The information contained in the "Regression statistics" output characterizes the "goodness" of the model as a whole. The quantities listed in this output can be expressed in terms of the regression F-number F_R (Table 4.3).

Standard Error (Sy) Sy = $(MS_E)^{1/2}$

MS_E is an error variance discussed before (equation 28).

Quantity S_Y is an estimate of the standard error (deviation) of experimental values of the dependent variable Y* with respect to those predicted by the regression model.

4.3 Coefficient of Determination

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Coefficient of Determination R^2 (or R Square): $R^2 = SS_R / SS_T = 1 - SS_E / SS_T$

SS_R, SS_E and SS_T are regression, residual (error) and total sum of squares.

The coefficient of determination is a measure of the regression model as whole. The closer R^2 is to one, the better the model (1) describes the data. In the case of a perfect fit $R^2 = 1$.

Adjusted coefficient of determination R^2 (or Adjusted R Square):

$R^2_{adj} = 1-\{SS_E / (n-k)\} / \{SS_T / (n-1)\}$

SS_E and SS_T are the residual (error) and total sum of squares. The significance of R^2_{adj} is basically the same as that of R_2 (the closer to one the better).

Multiple Correlation coefficient R

The fact that $R^2_{adj} = 0.870018$ in our illustration is fairly close to 1 (Table 11) suggests that overall model is GOOD to fit the experimental data presented in Table 3.3.

4.4 Validation Results

In table 4.1 and 4.2 selected parameter conditions both variable and dependent which determines the PV Module efficiency are displayed. Measured efficiency values were determined using Equation (35) the analysis demonstrated a favorable alignment between the model and data obtained from the existing PV Model.

The coefficient of determination (R^2), indicating the model's fit to the data, was found to be 0.893651.Table 4.6 and figure 4.7 present the comparative data used to assess efficiency, considering both experimental results and those derived from formulated performance models.

A statistical analysis comparing average predicted and measured efficiencies revealed no significant difference at a 95% level of Signicance. This was supported by the calculated Y value and Y* between the model and the data from the developed PV Module.

Table 4.10 the Measured and computed efficiencies for the PV module

PV Module (W)	Efficiency (%)	
	Computed	Measured
Jan	22	9.53
Feb	25	11.79
March	34	12.18

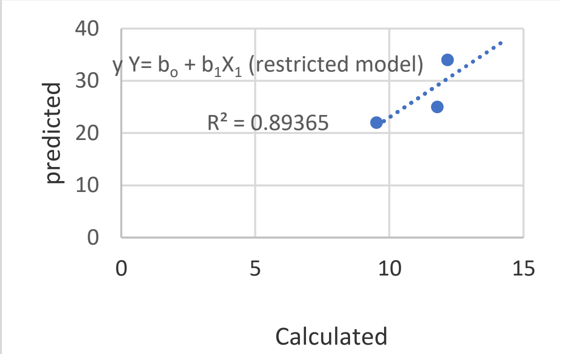

Figure 4.1: measured efficiency versus computed PV Module Efficiency

V. CONCLUSION

This study investigated the energy interaction and optimisation within a solar panel collector at peak hours of irradiation, with particular emphasis on Nigeria's climatic conditions and the need for improved photovoltaic (PV) system performance. By integrating theoretical analysis, experimental investigation, modelling, and statistical validation, the research provides a comprehensive understanding of the mechanisms governing solar energy conversion and the factors influencing PV efficiency during periods of maximum solar availability.

The findings demonstrate that solar photovoltaic technology represents a viable and sustainable solution for Nigeria's energy challenges, particularly in reducing reliance on fossil fuels and improving energy security. Nigeria's high solar irradiation potential, especially during peak sun hours, offers a significant opportunity for decentralized power generation capable of meeting residential, commercial, and rural energy demands. PV systems were shown to be especially beneficial for off-grid and underserved communities, contributing to improved socio-economic development through reliable electricity access for households, schools, healthcare facilities, and small industries.

A key outcome of the study is the establishment of a mathematical and physical framework describing energy interactions within PV collectors, including photon–electron interactions, semiconductor charge transport, and thermal effects. Governing relations such as the maximum kinetic energy equation for electron excitation and solar geometry expressions for declination angle, tilt angle, hour angle, zenith and azimuth angles were successfully applied to optimise solar energy capture during peak irradiation. These formulations enabled accurate prediction of system performance and provided a basis for improving collector orientation and configuration.

Experimental results confirmed that ambient temperature and solar radiation significantly influence PV module efficiency, with higher operating temperatures leading to reduced electrical output due to thermal losses. Regression and ANOVA analyses revealed a strong statistical relationship between climatic variables and module efficiency, with a coefficient of determination ($R^2 \approx 0.89$), indicating a high degree of agreement between measured and predicted performance. The developed optimisation model accurately captured efficiency trends, and validation results showed no significant difference between experimental and computed values at a 95 % confidence level.

The optimisation procedure demonstrated that maximum energy productivity occurs when PV systems are properly oriented, cooled, and configured to operate efficiently during peak sun hours. For the evaluated system, optimal efficiency was achieved under specific combinations of irradiance and ambient temperature, particularly for multi-crystalline silicon modules. The similarity between predicted and experimental efficiencies further confirms the reliability of the developed model and its applicability for system design and performance forecasting.

Overall, the study establishes that effective optimisation of PV collectors—through improved panel design, thermal management, orientation strategies, and system modelling—can significantly enhance energy capture during peak irradiation periods. These findings contribute to advancing solar energy deployment in hot and composite climates such as Nigeria and provide a technical foundation for future improvements in PV system design, efficiency enhancement, and large-scale implementation. The research therefore supports the broader goal of achieving sustainable, efficient, and environmentally friendly energy solutions to address Nigeria's growing electricity demand.

VI. RECOMMENDATIONS

The study recommends that Nigeria prioritize supportive policies and incentives to accelerate the adoption of PV solar module technology, including financial support, simplified regulations, and public awareness initiatives. A predictive model was developed to optimize PV efficiency by accounting for critical weather variations—such as temperature, humidity, dust, and insolation hours—across different geographical regions in Nigeria. Further research, including field trials and real-world performance monitoring, is advised to validate and refine PV module designs for regional conditions. Strong collaboration among academic institutions, research bodies, and industry stakeholders is essential to drive innovation, knowledge exchange, and capacity building. Continuous monitoring and evaluation of PV systems are necessary to ensure long-term performance and sustainability. Additionally, public-private partnerships should be promoted to attract investment, enhance commercialization, and improve the scalability and affordability of PV solar technology in Nigeria.

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