A PROJECT REPORT ON THE EFFECT OF TEMPERATURE ON SOLA R PANEL PERFORMANCE

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A PROJECT REPORT SUBMITTED TO PHYSICS UNIT, DEPARTMENT OF SC IENCE LABOURATORY TECHNOLOGY, INSTITUTE OF APPLIED SCIENCE (I AS)

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ABSTRACT

This study investigates the influence of temperature on the performance of solar panels. as solar panels convert sunlight into electrical energy, their efficiency is influenced by various environmental factors, including temperature. The project aims to examine the relationship between temperature and solar performance focusing on key parameters such as voltage, current and power output.

Experimental data is collected and analyzed to determine the extent to which temperature affects solar efficiency. the findings of this study provide valuable insights into optimizing solar panel design and operation for improved performance in diverse environmental conditions.

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We are also grateful to the rector, and the polytechnic management as well as the director, institute of applied sciences, for providing an enabling environment required for conducting worthwhile academic work in the form of lectures, projects, researches and extracurricular activities.

CERTIFICATION

This is to certify that the work was carried out and reported by YAHAYA NASIR UDEEN GALADIMA, ND/23/SLT/FT/0062 in the department of Science Laboratory Technology (SLT) Institute of Applied Sciences (IAS) and has been read and approved as meeting the requirement for the award of National Diploma (ND)

I. ________________ ___________________

Mr. Garba Muyideen Date

(Project Supervisor)

II. ________________ ___________________

Dr. Usman A. Date

(HOD, SLT)

III. ________________ ___________________

External Examiner Date

DEDICATION

We dedicate this project work to Almighty Godvi

DECLARATION

It is hereby declared that:

- This project has been prepared by us and that it is a record of our own research effort carried out under the supervision of Mr. Garba Muhyideen.
- To the best of our knowledge, it has neither been carried out nor presented in an y other institution of higher learning for certification
- All quotation and or citations and sources of information have been acknowled ged by means of references.

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CHAPTER 1

1.0 Introduction

1.1 Background on Solar Energy and Photovoltaics

Solar energy, derived from the electromagnetic radiation emitted by the sun, represents a virtually inexhaustible source of clean energy (Ahmad *et al.,* 2023). The sun's radiation reaches the Earth at an average rate of approximately 1361 W/m² at the top of the atmosphere (known as the Solar Constant) (ref: NASA). However, due to atmospheric scattering and absorption, the solar irradiance that reaches the Earth's surface varies depending on location, time of day, and weather conditions, typically ranging from 0 to 1000 W/m² at noon on a clear day (Mohapatra *et al.,* 2016). This variability necessitates careful consideration when designing and deploying solar energy systems (Patel *et al.,* 2022). This energy, fundamentally, arises from the nuclear fusion reactions occurring in the sun's core, primarily the fusion of hydrogen into helium, releasing immense amounts of energy in the process, with a reaction shown as:

$4\ {}^{1}H \rightarrow {}^{2}He + 2e^{+} + 2v_{e} + Energy$

Where ${}^{1}H$ represents hydrogen nuclei (protons), ${}^{2}He$ is the helium nucleus, e^{+} represents positrons, and v_{e} represents electron neutrinos. This energy is then radiated outwards, traversing the vast distance to Earth.

1.1.1 Brief Overview of Solar Energy Conversion

Solar energy conversion encompasses various methods to transform solar radiation into usable forms of energy, such as electricity, heat, and chemical energy (Patel *et al.,* 2022). Common methods include solar thermal collectors (for heat generation), photovoltaic (PV) systems (for electricity generation), and solar chemical processes (e.g., photocatalysis).

- Solar Thermal Collectors: These devices absorb solar radiation to heat a working fluid (e.g., water or oil), which can then be used directly for space heating, water h eating, or as a source of energy for industrial processes or electricity generation (e.g., through steam turbines).

- Solar Chemical Processes: These use solar energy to drive chemical reactions, su ch as the splitting of water into hydrogen and oxygen for fuel production or for in dustrial chemical processes (Yadav *et al.*, 2018).

- Photovoltaic (PV) Conversion: This is the most common method of solar energy conversion to electricity and is the primary focus of this project. It will be discuss ed in further detail in the following section (Chopra *et al.,* 2020).

1.1.2 Introduction to the Photovoltaic Effect

The photovoltaic effect is the fundamental physical phenomenon underlying solar ce ll

operation (Tiwari *et al.*, 2021). It describes the generation of a voltage and electric cur rent in a material when exposed to electromagnetic radiation (light), typically when p hotons in sunlight are absorbed in a semiconductor material (usually crystalline silico n). When a photon with energy greater than the material's band gap (the minimum en ergy needed to excite an electron) hits a solar cell, it can excite an electron, causing it to jump from the valence band to the conduction band, creating a free electron and a "hole," effectively a positive charge. This process is best described using quantum me chanics, as we move from a bound electron in a silicon crystal lattice to a free carrier (Chaturvedi *et al.,* 2020). The basic equation for the process, expressed in terms of en ergy can be stated as:

$E_{photon} = hf \geq E_g$ (or $E_{photon} = hc/\lambda \geq E_g$)

Where E_{photon} is the photon energy, h is Planck's constant (approximately 6.626 x 1

0⁻³⁴ J·s), f is the frequency of the light, c is the speed of light (approximately 3×10^8 m/s), λ is the

wavelength of light, and E_g is the band gap energy of the semiconductor material (a pprox. 1.1 eV for silicon).

1.1.3 Basic Structure of Solar Cells and Panels

A typical solar cell is constructed from a semiconductor material, often crystalline sili con (cSi), that has been treated to create a p-n junction. This p-n junction is an interfa ce between two differently doped semiconductors, an n-type material (with an excess of free electrons) and a p-type material (with an excess of "holes"). The key to operati on is that the built-in electric field at this junction separates the electron-hole pairs cre ated by the absorbed photons

(Chaturvedi *et al.,* 2020).

- Front Contact: A grid-like metallic contact on the front of the solar cell allows for t he collection of the electrons generated. This is usually designed to minimize sha ding, by covering only small area.

- Semiconductor Material: The p-n junction is the active part of the cell, made of sp ecially treated semiconductor materials (Mehta *et al.,* 2017). In addition to silicon, other materials such as gallium arsenide (GaAs) and cadmium telluride (CdTe) ar e also used.

- Back Contact: A metallic contact on the back of the cell acts as a collector for the holes. Individual solar cells are electrically interconnected to form solar modules or panels (Joshi *et al.,* 2019). Multiple solar panels are then connected to form so lar arrays in real world applications. These connections are typically arranged in s eries or parallel to increase voltage or current output as needed.

Approximate Values and Calculations:

- Band Gap of Silicon (E_g): Approximately 1.1 eV (electron volts)
- Wavelength of Maximum Solar Irradiance (λ): Around 550 nm (nanometers). This corresponds to the peak of the visible light spectrum.
- Energy of a Photon at 550 nm: $E = hc/\lambda = (6.626 \times 10^{-34}\ J\cdot s \times 3 \times 10^{8}\ m/s) / 550 \times 10^{-9}\ m \approx 3.6 \times 10^{-19}\ J$ (approx 2.25 eV)
- Approximate Efficiency of Commercial Solar Panels: Ranges from 15% to 22% fo r common silicon-based panels.
- Peak Solar Irradiance on Earth: On a clear sunny day it can reach ~1000 W/m^2.
- Power Output from a Single Panel (example): A typical commercial solar panel wi th 1 m^2 area can generate a peak output of around 150-250W (depending on the t echnology) in peak sunlight.

1.2 Temperature Dependence of Solar Panel Performance

The performance of solar photovoltaic (PV) panels is significantly influenced by their operating temperature. Unlike many electrical devices that perform optimally at a spe cific temperature, solar cells tend to exhibit a decrease in performance as their temper ature increases. This temperature sensitivity arises from the inherent physics of semi conductor materials and directly affects critical parameters such as voltage, current, and ultimately, the power output of the solar panel (Grover et al., 2021). This section will delve into the underlying causes of this phenomenon, its practical implications, a nd the means to mitigate its impact.

1.2.1 Factors Affecting Solar Panel Efficiency

Solar panel efficiency, denoted as η, which is the ratio of electrical power output to solar power input (i.e., incident light on panel) is affected by a multitude of factors. The most pertinent in this discussion is the operating temperature of the panel (Soni *et al.,* 2023).

- Band Gap Energy Reduction: The band gap energy (Eg) of a semiconductor material, such as silicon, is temperature-dependent. The band gap energy decreases with increasing temperature. The empirical equation shows that the band gap of silicon varies approximately as:

4Eg(T) = Eg(0) - αT

where Eg(T) is the band gap energy at temperature T, Eg(0) is the band gap energy at absolute zero (0 K), and α is a temperature coefficient (≈ 2.4×10^{-4} eV/K for silicon).

This reduction in band gap with increasing temperature means that electrons require less energy to jump to the conduction band. This results in more charge carriers, leading to an increase in short circuit current (Isc), but unfortunately at the same time, the open-circuit voltage (Voc) reduces dramatically, which reduces the overall power output. The reduction in Voc dominates so the overall panel efficiency drops with increase in temperature (Sharma *et al.,* 2019).

- Increased Recombination: Higher temperatures increase the vibrational energy of atoms in the semiconductor material. This increased atomic motion makes it more likely that charge carriers (electrons and holes) will recombine within the material (before they are collected), reducing the number of free carriers available to contribute to the current (Sagar *et al.,* 2021). This increases the recombination current, which reduces the Isc and Voc.

- Carrier Mobility: Temperature impacts the mobility of charge carriers (electrons and holes). At higher temperatures, lattice vibrations become more prominent. As t he charge carriers move through the material, they can interact with the vibrating atoms, leading to scattering and reduced mobility. This decreases the conductivity of the solar cell, and thereby the current it can produce (Rana *et al.*, 2020).

- Series Resistance: Temperature affects the resistance of the materials within the solar cell,

including the semiconductor, metallic contacts, and connecting wires (Garg *et al.,* 2017). Increased temperature often leads to an increase in the series resistance of the cell (due to reduced mobility), further reducing power output.

1.2.2 Significance of Temperature Effects on Solar Cell Performance

The practical significance of temperature effects is profound and influences many design

considerations:

• Reduced Power Output: As the temperature of a solar panel increases, its power output decreases. This is primarily due to the reduction in open-circuit voltage (Voc) being more significant than the increase in short-circuit current (Isc). For crystalline silicon solar cells, the reduction in power output is approximately 0.3-0.5% per degree Celsius increase above standard test conditions (STC), often around 25°C [5]. This number is captured in the temperature coefficient of power output, usually shown as a %/°C, by manufacturers, making

it an important design consideration (Mohanraj *et al.,* 2019).

- Efficiency Reduction: The overall energy conversion efficiency decreases with temperature. Since temperature coefficients for common crystalline silicon are negative, the panel efficiency drops with increase in temperature, so panels are less efficient in warmer climates (Kumar *et al.*, 2018).

For example, a panel with a nominal efficiency of 20% at 25°C may only operate at 16-17% if the temperature rises above 65-75°C.

- Hot Spots and Reliability: Uneven temperature distribution across a panel (due to shading or poor ventilation) can lead to the formation of "hot spots," localized areas of higher temperature. These spots can cause damage to the panel's materials, reduce its lifespan, and cause degradation in performance (Sharma *et al.*, 2020).

- Design and Installation Considerations: Understanding the temperature dependence is essential for designing solar arrays that maximize energy production under different climatic conditions. This involves strategies for heat dissipation, efficient ventilation, and careful placement of the solar arrays (Singh *et al.,* 2022).

Calculations:

- Approximate Temperature Effect: Assume a panel with a power output temperature coefficient of -0.4%/°C at STC (25°C). If the panel temperature reaches 55°C, the power output will decrease by: (55°C - 25°C) × (-0.4%/°C) = -12%. Meaning the actual power output will be 88% of its rated peak output.

Approximate Values:

- Temperature Coefficient of Power: Typically -0.3 to -0.5 %/°C for c-Si solar panels.

- Open-Circuit Voltage (Voc) Temperature Coefficient: Approximately -2 mV/°C to -3 mV/°C for silicon solar cells. This is an empirical value, not a material property.

- Short Circuit Current (Isc) Temperature Coefficient: Approximately +0.04 to +0.06 %/°C for c-Si solar cells.

- Normal operating temperature range of PV panels The panels can be operating in the range of -40°C and +85°C and with surface temperatures above 100 °C possible i n hot sunny climates.

1.3 Research Motivation and Scope

The imperative to transition towards sustainable energy sources has never been more critical, and solar photovoltaics (PV) stands as a key technology in this shift. While significant advancements have been made in solar panel technology, understanding and mitigating the temperature-dependent performance of solar panels remains a critical challenge to optimize their efficiency and reliability in real-world conditions. This research is driven by the need to address these challenges by investigating the impact of temperature on various performance parameters of solar cells (Dhar *et al.*, 2018).

1.3.1 Importance for Solar Energy Applications

The temperature dependence of solar panel performance has profound implications for the scalability, economic viability, and overall success of solar energy applications (Wang *et al.*, 2016).

- Optimizing System Design: Accurate understanding of how temperature affects solar panel efficiency is crucial for system design. This information enables the development of more effective strategies for cooling, system integration, and power management, thereby maximizing energy production (Ramanathan *et al.*, 2015). This involves selecting suitable panels for the location, or active panel cooling (active air ventilation, water cooling) to offset temperature effects.

- Enhancing Energy Output: Temperature effects can severely limit solar energy production, especially in hot climates. By reducing the performance degradation caused by heat, we can make PV systems more productive and reliable, thereby increasing their return on investment and overall environmental impact (Kim *et al.*, 2017).

- Improving Reliability and Lifespan: Prolonged exposure to high temperatures, especially at localized hotspots can accelerate degradation and reduce the lifespan o f solar panels. Research on temperature effects informs the design of more robust panels that are less susceptible to thermal damage (Zhang *et al.,* 2021). This is achieved by both passive (materials and construction choices) and active (cooling solutions, management systems) mitigation strategies.

- Predictive Modeling: A better understanding of how temperature affects solar cell performance is necessary for creating more accurate predictive models. These models enable better projections of energy output and financial planning of solar panel installations (Cui *et al.,* 2018).

- Grid Stability: With increased penetration of solar energy into the power grid, accurately predicting their energy output is crucial for grid stability. Variability caused by temperature 8changes is a significant factor that must be taken into consideration (Jain *et al.,* 2019).Understanding this variability helps in better grid management.

- Wider Deployment: If we can address the issue of temperature dependence, this will increase the suitability of solar energy in a wider range of climates, extending its applicability to various regions.

1.3.2 Objectives of this Project

This research project aims to provide a thorough and systematic investigation into the effects of temperature on solar cell performance. The primary objectives are:

1. Quantify the Relationship: To experimentally determine and quantify the relationship between temperature and key solar cell performance parameters including open-circuit voltage (Voc), short-circuit current (Isc), maximum power point (Pmax), and overall panel efficiency. The target temperature range will be between 20°C and 80°C (typical operating conditions).

2. Analyze I-V Characteristics: To analyze how the current-voltage (I-V) characteristic

s of solar cells change under different temperature conditions. This involves carefully measuring and analysing the I-V characteristics at the various controlled tempera tures.

3. Evaluate Temperature Coefficients: To determine and validate the temperature co efficients (the change in performance per degree Celsius) for different key solar c ell parameters. These coefficients will be compared with manufacturer's specific ation if available and used to predict performance at given temperatures.

4. Identify Potential Improvements: To gain insights into how temperature effects c an be mitigated through different active and passive measures or design choices. This would involve a review of current mitigation techniques.

5. Validate Theoretical Predictions: To compare experimental results with theoretica l predictions to validate and refine existing models of solar cell behavior under th ermal stress. Specifically focusing on semi-conductor properties, such as bandga p, mobility, and intrinsic concentration, with increasing temperature.

CHAPTER 2

2.0 Theoretical Background

2.1 Semiconductor Physics and the Photovoltaic Effect

The photovoltaic effect, the cornerstone of solar energy conversion, is deeply rooted i n the physics of semiconductor materials. Understanding the underlying principles of semiconductor behavior, particularly the formation of p-n junctions and their interacti on with light, is critical for comprehending the operation of solar cells. This section wi ll delve into the core concepts of semiconductor physics that govern the photovoltaic effect.

2.1.1 Energy Bands, Doping, and p-n Junctions

Semiconductors, unlike conductors or insulators, possess electrical conductivity that can be controlled by introducing impurities. The energy levels of electrons in a crystal line material are organized into bands (Rincón & González, 2014).

- Energy Bands: Electrons in solids occupy specific energy bands. Two crucial ban ds are the valence band, the highest band filled with electrons at absolute zero, a nd the conduction band, which is the next higher band where electrons can move freely to conduct current (Yang *et al.,* 2022). The energy gap between the valence and conduction bands is called the band gap (Eg). In a semiconductor, this band gap is relatively small (around 1.1 eV for silicon).

- Intrinsic Semiconductors: In pure or intrinsic semiconductors, like silicon (Si), the number of electrons in the conduction band is equal to the number of holes in the valence band (electronhole pairs). This is because, at room temperature, some ele ctrons in the valence band are excited by thermal energy to cross the band gap to reach the conduction band, leaving holes behind (Lee & Kang, 2014). The concent ration of these carriers (intrinsic concentration n_i) is given as:

$n_i = \sqrt{(N_C N_V)} * e_{(-Eg/2kT)}$

Where Nc is the effective density of states in the conduction band, Nv is the effective density of states in the valence band, Eg is the band gap energy, k is the Boltzmann c onstant (approximately 1.38×10^{-23} J/K or 8.617×10^{-5} eV/K), and T is the absolute t emperature (Kumar & Sharma, 2013).

- Doping: The conductivity of semiconductors can be increased significantly by int roducing impurities, a process known as doping. There are two types:
- n-type Doping: Introducing impurities with more valence electrons than the semic onductor material (e.g., phosphorus (P) in silicon) creates n-type material (Vyas *et al.,* 2021). These impurity atoms (donors) donate extra electrons into the conduct ion band, increasing the concentration of free electrons, denoted as n.
- p-type Doping: Introducing impurities with fewer valence electrons than the semic onductor material (e.g., boron (B) in silicon) creates p-type material (Li *et al.,* 202 0). These impurity atoms (acceptors) create "holes" in the valence band, increasin g the concentration of holes, denoted as p.
- p-n Junction: A p-n junction is formed when a p-type and an n-type semiconducto r material are brought into contact (Ahn *et al.,* 2012). The following process takes place at the junction:
- Diffusion: The high concentration of electrons in the n-type material diffuse to th e p-side and the high concentration of holes in the p-side diffuse into the n-side.
- Space Charge Region: This diffusion creates a depletion or "space charge" region with a built-in electric field at the junction due to the positively charged donors an d negatively charged acceptors that remain (Zhao *et al.,* 2015).

- Equilibrium: When equilibrium is reached, the diffusion current of carriers is balanced by the drift current induced by the electric field at the junction. This field separates any photogenerated electron-hole pairs (Zhao *et al.,* 2015).

2.1.2 Photon Absorption and Electron-Hole Generation

The photovoltaic effect is initiated by the absorption of photons with sufficient energy to generate electron-hole pairs (Srinivasan *et al.,* 2017).

- Photon Absorption: When a photon with energy ($E_{photon} = hf = hc/\lambda$) greater than the band gap energy (Eg) strikes a semiconductor material, it can excite an electron in the valence band to the conduction band. The electron is now free to move, and a hole is left behind in the valence band (Tiwari *et al.,* 2013).

- Electron-Hole Pair Generation: The process results in the generation of electron-hole pairs. In a solar cell, this occurs in and around the depletion region (Tiwari *et al.*, 2013).

- Quantum Efficiency: Not every photon is absorbed and creates an electron-hole pair. The efficiency of this process is known as the quantum efficiency (Lal *et al.,* 2016). Some photons are reflected, or not absorbed (due to the material, photon energy, etc), and the electron hole pairs can also recombine before collection.

2.1.3 Current-Voltage (I-V) Characteristics of Solar Cells

The current-voltage (I-V) characteristic of a solar cell describes how the current flowing through the cell varies with the applied voltage (IEA, 2022). The solar cell's behaviour is that of a current source, not a voltage source.

- Short-Circuit Current (Isc): This is the current flowing through the cell when the voltage across its terminals is zero (NREL, 2023). This occurs when there is a direct short-circuit (zero resistance) across the terminals. The magnitude of this current is proportional to the photon flux incident on the solar cell.

- Open-Circuit Voltage (Voc): This is the voltage across the cell terminals when no current flows through it (open circuit). The voltage arises from the separation of t he charge carriers in the p-n junction. This voltage corresponds to the maximum potential difference the cell can provide (Bost *et al.,* 2016).

- Maximum Power Point (MPP): The product of current and voltage is the power de livered (Meyers *et al.,* 2010). The cell delivers a maximum power at a point (Vmp, Imp) along the I-V curve where the product of current and voltage is maximized (i. e., P=I × V). This is the power output that we want the cell to deliver (Chen *et al.,* 2 020).

- Fill Factor (FF): The fill factor is a measure of the squareness of the I-V curve and is the ratio of maximum power output (Pmax) to the product of Isc and Voc:

  $FF = P_{max} / (Isc * Voc)$

Formulas

- Current density across a PN junction

  J = Jo (exp(eV/nkT) - 1) - J_L

where Jo is the reverse saturation current density, e is the fundamental electron charg e, V is the applied voltage, n is the ideality factor (usually between 1 and 2), k is the B oltzmann constant, T is the absolute temperature, and J_L is the photo generated curr ent density.

Calculations and Approximations

- Band Gap of Silicon (Eg): Approximately 1.1 eV (electron volts) at room temperat