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Efficiency Analysis of Small Solar Cells Under Varying Light Intensities and Angles

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Abstract
The efficiency and performance of small solar cells are strongly influenced by light intensity, angle of incidence, and the type of illumination. This study investigates the electrical characteristics of silicon-based small solar cells under mixed indoor and outdoor conditions, using both LED and sunlight simulation. Experiments were conducted at light intensities ranging from 100 lux to 100,000 lux and tilt angles from 0° to 75°, measuring open-circuit voltage (Voc), short-circuit current (Isc), maximum power (Pmax), fill factor (FF), and overall efficiency. Results indicate that increasing light intensity enhances voltage, current, and power output, while tilt angle adversely affects performance, with the greatest efficiency losses observed at low intensities and extreme angles. Sunlight simulation provided higher performance metrics compared to LED lighting, demonstrating its robustness for outdoor applications. The study also highlights the feasibility of energy harvesting under low-light indoor conditions for IoT and low-power devices, albeit with sensitivity to orientation. These findings provide essential insights for optimizing small solar cell deployment in mixed indoor–outdoor environments and for designing energy-efficient micro-electronic systems.
Keywords: *small solar cells, light intensity, incident angle, energy harvesting, IoT devices*

I. Background and Context

Solar photovoltaic (PV) technology has become one of the most rapidly expanding renewable energy solutions in the world. The global transition toward sustainable energy sources, the depletion of fossil fuels, and growing concerns regarding climate change have significantly increased interest in solar-based systems. Within the broader PV sector, **small solar cells**—including miniature cells used in sensors, portable electronics, Internet-of-Things (IoT) devices, educational kits, and low-power embedded systems—represent a critical technological component. These small-scale energy harvesters are increasingly deployed in off-grid applications where conventional wiring or frequent battery replacement is impractical. To improve the performance of these systems, understanding how small solar cells behave under **varying environmental conditions**, particularly different **light intensities** and **incident angles**, has become essential.

Solar cell efficiency, defined as the fraction of sunlight converted into usable electrical energy, depends heavily on the quantity and quality of the incident light. Traditionally, most laboratory characterizations of solar cells are performed under Standard Test Conditions (STC), which assume a fixed irradiance of 1000 W/m², a cell temperature of 25°C, and an Air Mass (AM) 1.5 spectral distribution. However, real-world operating conditions rarely match these standardized parameters. In practical use, small solar cells may receive fluctuating light levels due to shading, movement, atmospheric variations, or changes in the orientation of the cell with respect to the sun or artificial light sources. Therefore, performance characteristics under diverse conditions can be significantly different from what manufacturers report. In many applications—such as wearables, remote sensors, solar-powered calculators, traffic devices, solar toys, emergency gadgets, garden lights, and miniature chargers—small solar cells are not mounted at optimal angles. Instead, they often operate indoors or under diffused sunlight, where the spectral composition and intensity of light vary significantly from natural sunlight. Because of these variations, **comprehensive efficiency analysis** across a range of intensities and orientation angles is necessary to estimate real-life performance and to design improved systems for maximum power extraction.

II. Importance of Studying Small Solar Cells

Small solar cells, due to their compactness, portability, and affordability, have become an integral part of modern energy-harvesting systems. Their ubiquity arises from the increasing demand for self-powered devices that require only minimal electrical inputs to operate. IoT devices, for instance, are expected to number in the tens of billions within the coming years. Many of these devices will be deployed in environments where replacing batteries is inconvenient or impossible. Small PV units offer a sustainable solution by continuously harvesting ambient energy. Moreover, small solar cells are used extensively in educational and experimental environments to demonstrate fundamental PV principles. Their controllable size and low operational risk make them suitable for laboratory investigations where variables such as intensity, angle, and shading can be adjusted easily. In research, small solar cells serve as a proxy for larger PV modules to study underlying physical principles without requiring larger or more expensive testbeds. They are also ideal for studying rapid transient responses to changing light conditions because their lower thermal inertia helps them adapt quickly. However, despite their widespread adoption, the efficiency and performance of small solar cells under non-uniform illumination conditions are often underreported. Manufacturers typically provide efficiency values measured under ideal conditions, leaving end-users with limited guidance on how these cells actually behave in diverse environments. Since most real-world applications involve dynamically varying lighting, especially for mobile or wearable devices, empirical studies on efficiency under varying intensities and angles become crucial.

III. Solar Cell Working Principles and Relevance to Efficiency

Solar cells operate on the photovoltaic effect, where photons striking the cell material excite electrons, generating electron–hole pairs that produce an electric current. The efficiency of this conversion depends on multiple internal and external factors:

- **Material properties** (silicon, GaAs, thin-film materials, organic solar cells)
- **Cell structure and surface texture**
- **Junction quality**
- **Temperature and internal resistances**
- **Spectral composition of light**
- **Intensity and angle of incidence**

The intensity of light determines how many photons are available to generate charge carriers. Higher intensity generally increases short-circuit current but may saturate performance due to recombination losses or increased temperature. Conversely, lower intensities reduce output and may lower voltage significantly. The angle of incidence changes the amount of light reaching the cell surface. Maximum irradiance occurs when light is perpendicular to the surface; any deviation introduces cosine losses, reflection, and uneven illumination across the cell surface. Another factor is the spectral distribution of the light source. Indoor lights, for example, often emit in narrower spectral bands, leading to reduced voltage and efficiency compared to natural sunlight. Because small solar cells are often used indoors or in hybrid environments, variations in spectral composition further complicate their efficiency characteristics.

IV. Light Intensity Variation and Its Effect on Small Solar Cells

Light intensity, commonly measured in lux (for visual brightness) or W/m² (for actual irradiance), is a major determinant of solar cell output power. Under increasing light intensity:

- **Short-circuit current (Isc)** rises almost linearly because more photons generate more charge carriers.
- **Open-circuit voltage (Voc)** increases logarithmically due to the diode equation.
- **Power output** increases but may saturate at high intensities due to thermal losses and recombination.

Under low-intensity conditions, small solar cells may exhibit disproportionately low performance. For instance, in indoor lighting (100–500 lux), the irradiance is significantly lower compared to sunlight (100,000 lux), resulting in minimal current generation. Many small solar cells are not optimized for indoor spectra, giving them low voltages that may fall below operational thresholds for certain devices. This makes efficiency data under **varied intensities** crucial for real-world design. Additionally, the response of small solar cells to rapid fluctuations (such as passing clouds or moving objects) is important. Because these cells have low mass and area, they respond quickly to changes, making them a reliable model for studying transient effects that mimic the dynamic behavior of larger PV systems.

V. Influence of Angle Variation on Solar Cell Output

The angle of incident light affects the cell's ability to absorb photons efficiently. The relationship follows **Lambert's cosine law**, which states that intensity is proportional to the cosine of the angle between the incoming radiation and the cell's normal vector. At 0° (perpendicular), solar cells receive maximum irradiance. Beyond this point, the effective area exposed to radiation decreases, reducing output. At higher tilt angles:

- **Reflection losses** increase.
- **Photon absorption decreases.**
- **Voltage and current drop.**
- **Power output falls faster than intensity due to combined optical and electrical losses.**

Dust accumulation, surface imperfections, and uneven illumination also increase at higher angles. These effects are more pronounced in **small solar cells**, where the area is minimal and any localized loss can affect the total output significantly. Additionally, small cells often lack protective coatings or tracking mechanisms used in large PV modules, making angle optimization more challenging. Small solar-powered devices frequently operate at angles determined by user behavior rather than engineering design (e.g., wearable devices, handheld gadgets, mobile sensors). Therefore, understanding how angular variation impacts efficiency is essential for predicting performance under realistic usage conditions.

VI. Need for Efficiency Analysis Under Realistic Conditions

Conventional laboratory reports of solar cell efficiency rarely reflect real-world needs. Small solar cells deployed in dynamic environments may experience:

- Shaded areas
- Partial occlusion from the user
- Reflection from nearby surfaces
- Rapid movement
- Indoor-to-outdoor transitions
- Light from non-solar sources (LEDs, fluorescent lamps, etc.)

Each of these conditions influences performance. Only by testing under variable intensities and angles can researchers understand the full operational capability of small solar cells.

Efficiency analysis under such conditions is essential for:

- **Designing better deployment strategies**
- **Choosing appropriate power management circuits**
- **Estimating realistic battery charging times**
- **Developing maximum power point tracking (MPPT) algorithms**
- **Creating energy-harvesting systems for IoT and wearables**
- **Improving manufacturing and material design**

In many low-power systems, even slight drops in efficiency can lead to functional issues. For example, an IoT sensor that requires 10 mW may fail to operate if the solar cell provides only 8 mW due to poor orientation or dim lighting. Thus, device reliability hinges on accurate efficiency prediction.

VII. Types of Small Solar Cells and Their Response to Changing Conditions

Small solar cells are made using different technologies, each with unique efficiency profiles:

1. Monocrystalline Silicon Cells

- High efficiency (typically 15–22%)
- Good performance under direct sunlight
- Moderate sensitivity to angle changes
- Poor performance under artificial lighting

2. Polycrystalline Silicon Cells

- Moderate efficiency
- Slightly more tolerant to temperature variations
- Often used in educational kits and low-cost devices

3. Amorphous Silicon (a-Si) Cells

- Better performance under low-intensity light
- Flexible and lightweight
- More tolerant to shading and angle variations
- Lower overall efficiency compared to crystalline cells

4. Organic and Dye-Sensitized Solar Cells (DSSC)

- Perform well under indoor and diffused lighting
- Very sensitive to temperature
- Angle-dependent efficiency varies by design

Because of these variations, the choice of cell type influences performance under varying intensity and angle conditions. Efficiency analysis therefore helps determine the best cell type for specific real-world applications.

VIII. Concept of Efficiency and Power Output

Efficiency of a solar cell is computed as:

$$\text{Efficiency} = \frac{P_{out}}{P_{in}} \times 100$$

Where:

- Pout=V×I is the actual electrical power generated
- Pin is the incident solar power, calculated using irradiance and cell area

However, efficiency depends not only on intrinsic material properties but also on:

- Fill factor (FF)
- Series and shunt resistances
- Spectral mismatch
- Temperature
- Optical losses
- Operating point relative to maximum power point (MPP)

In small solar cells, the fill factor and series resistance play a larger role because their material layers are thinner and more susceptible to recombination. At low intensities, internal resistance dominates, reducing voltage and thereby lowering efficiency. Similarly, deviations in incident angle result in losses due to increased reflection and decreased absorption.

IX. Light Intensity–Voltage–Current Relationship

In a solar cell **Current (I)** increases linearly with light intensity **Voltage (V)** increases logarithmically AND **Power (P)** is a combination of these relationships. When intensity is reduced Voltage decreases significantly. Power output declines sharply. AND Efficiency becomes lower due to increased proportion of recombination losses. This nonlinear behavior means that power output does not fall proportionally with light reduction, which is crucial for systems that rely on continuous energy harvesting.

X. Angle–Intensity Interaction

As the solar cell's tilt angle increases:

- Effective irradiance reduces according to the cosine law.
- Light may reflect from the surface, causing additional loss.
- The spectrum of absorbed light may change due to refraction effects.

Additionally, real-world lighting often does not follow ideal geometric patterns. Artificial lights may illuminate the cell from multiple directions, creating complex angle–intensity interactions. For small solar cells placed indoors, the angle may matter less because of diffused light, but for outdoor use, even a small deviation from perpendicular orientation can cause substantial performance drops.

XI. Practical Relevance in Modern Technology

The transition to smart systems and low-power electronics has made small solar cells an indispensable component in modern engineering. Some major uses include:

- **Wearable technology-**Solar-powered smartwatches, health trackers, and outdoor safety devices rely on small PV cells. Their orientation changes continuously, making angle-dependent efficiency crucial.
- **IoT sensors and communication nodes-**Agricultural sensors, environmental monitors, and smart-city devices often receive indirect sunlight or are placed at inclined angles.
- **Educational and DIY systems-**Students and hobbyists use small solar cells in experimental setups where light intensity control is essential.
- **Portable electronics-**Solar lights, emergency chargers, and mini-power systems operate in variable lighting environments.
- **Robotics-**Small robots and drones sometimes rely on onboard solar panels to extend operational times.

Understanding how intensity and angle affect these cells enables reliable design, optimal deployment, and efficient energy harvesting.

XII. Research Gap

Despite the wide usage of small solar cells, existing research suffers from several gaps:

1. **Insufficient experimental data** on small cells under varied intensities and angles.
2. **Most studies focus on full-size PV modules**, not miniature cells.
3. **Indoor lighting conditions are underexplored**, even though many small cells operate indoors.
4. **Angle-dependent spectral effects** are rarely studied for small cells.
5. **Manufacturers provide inadequate real-world performance data** for non-standard conditions.

A systematic analysis can help fill these gaps and offer valuable insights for designers, engineers, hobbyists, and scientists.

XIII. Problem Statement

Small solar cells used in low-power electronics often operate in environments with varying light intensities and angles, significantly affecting their actual output and efficiency. However, there is limited experimental data capturing how these variations impact real-world performance. Without such analysis, designers and users cannot accurately estimate the energy-harvesting capabilities of small solar cells or optimize their placement for maximum output.

XIV. Objectives of the Study

The primary objectives include:

1. To measure and analyze the output performance (voltage, current, and power) of small solar cells under different light intensities.
2. To determine how angle variation affects efficiency and power output.
3. To compare overall efficiency trends at different combinations of intensity and angle.
4. To identify optimal operating conditions for small solar cells.
5. To understand practical limitations under indoor and outdoor lighting environments.
6. To develop a performance profile that helps predict real-world behavior.

XV. Scope of the Study

This study focuses specifically on:

- Small silicon-based solar cells (mono/polycrystalline or amorphous, depending on availability)
- Indoor and artificial light environments as well as outdoor simulations
- Light intensities ranging from low (100 lux) to high (100,000 lux)
- Angle variations from 0° to 90°

The study does not address long-term degradation, temperature effects, or spectral characterization in detail, though these factors are acknowledged.

XVI. Significance of the Study

The findings will:

- Aid engineers in designing efficient low-power solar systems.
- Help students and researchers understand PV characteristics more deeply.
- Improve the reliability of solar-powered IoT devices.
- Provide essential data for selecting and positioning solar cells in various applications.
- Enhance decision-making in industries developing consumer electronics.

Moreover, as the world moves toward autonomous smart technologies, this analysis becomes increasingly important for sustainable electronics and renewable micro-power generation.

EXPERIMENTAL SETUP

The experimental setup for analyzing **efficiency of small solar cells under varying light intensities and angles** involves a combination of controlled indoor experiments and sunlight simulation to replicate realistic conditions. The primary aim is to quantify the effects of light intensity and incidence angle on the photovoltaic performance parameters, including voltage (Voc), current (Isc), output power (P), fill factor (FF), maximum power point (Pmax), and efficiency (%).

1. Solar Cell Specifications

The experiments were conducted using **small silicon-based solar cells** with an area of 4 cm^2. The cells were chosen for their reproducibility and widespread availability. Electrical characteristics were recorded using a **digital source meter** capable of measuring micro-voltages and milli-amperes accurately. Cells were mounted on a **rotatable platform** to vary angles precisely from 0° (perpendicular incidence) to 75° in 15° increments.

2. Light Sources

Two types of illumination were used:

1. **LED Lighting**: For indoor low-intensity tests, LEDs with calibrated lux outputs of 100, 500, 1,000, and 5,000 lux were employed. Lux meters ensured accurate measurement of incident light on the cell surface.
2. **Sunlight Simulation**: High-intensity solar simulators provided outdoor-equivalent irradiance levels of 20,000 and 100,000 lux, replicating full sunlight conditions. The simulator used a **Xenon arc lamp** with uniform beam distribution.

3. Measurement Instruments

- **Digital Multimeter/Source Meter**: Measured Voc and Isc with ±0.1% precision.
- **Lux Meter**: Ensured correct light intensity at the cell surface.
- **Angle Measurement**: A high-precision protractor and rotatable mount allowed accurate tilting.
- **Data Logger**: Recorded time-dependent voltage and current to compute Pmax and efficiency.

4. Experimental Procedure

1. The solar cell was placed on the **rotatable platform** inside a dark enclosure to prevent stray light interference.
2. For LED tests, the light source was positioned at a fixed distance to achieve the desired lux levels. Lux meters verified intensity at the cell surface.
3. The **cell was rotated** from 0° to 75° in 15° increments, and for each angle, **Voc and Isc** were measured.
4. Output power was calculated as P=V×I, and efficiency was computed using:

$$\text{Efficiency (\%)} = \frac{P_{\text{out}}}{P_{\text{in}}} \times 100$$

where Pin is incident power per unit area (converted from lux to W/m²).

5. Measurements were repeated three times for each condition to ensure reliability.

5. Sunlight Simulation Setup

For high-intensity tests, the solar simulator was used with adjustable beam distance to achieve target lux. Thermal effects were mitigated using **heat sinks and airflow**, maintaining cell temperature at 25 ± 2°C to avoid thermal-induced variations. Voltage and current were measured similarly for each tilt angle.

6. Data Processing

Recorded data for Voc, Isc, and Pmax were tabulated. Fill factor was calculated using:

$$FF = \frac{P_{\text{max}}}{V_{\text{oc}} \times I_{\text{sc}}} \times 100$$

Efficiency drop and power loss percentages were derived to evaluate the effect of angle. Graphs of voltage, current, power, and efficiency versus angle and intensity were plotted to visualize trends.

- **Ambient light exclusion**: Indoor tests were conducted in a dark room to prevent interference.
- **Stabilized light source**: LED and sunlight simulators were allowed to stabilize for 10 minutes before measurement.
- **Repeated trials**: Each experiment was repeated at least three times to reduce random errors.
- **Temperature monitoring**: A thermocouple measured cell temperature, ensuring consistent thermal conditions.

All electrical measurements were conducted with insulated cables and grounding to prevent short circuits. Instruments were calibrated prior to experiments. Lux meters and solar simulators were cross-verified against reference solar cells.

Experimental Flow

1. Mount solar cell on rotatable platform.
2. Set light source to desired intensity.
3. Adjust angle from 0° to 75°.
4. Measure Voc, Isc, compute P, Pmax, FF, and efficiency.
5. Record data for LED and sunlight separately.
6. Repeat trials for reproducibility.
7. Analyze efficiency and performance trends with intensity and angle.

This setup allows **comprehensive characterization** of small solar cells under mixed indoor and outdoor lighting, capturing the combined effects of **light intensity, incident angle, and source type** on voltage, current, power, and efficiency. It is ideal for IoT and low-power electronics studies where both indoor and outdoor harvesting is critical.

TABLE 1: Open-Circuit Voltage (Voc) at Different Light Intensities & Angles

Light Intensity (lux)	0° (V)	15° (V)	30° (V)	45° (V)	60° (V)	75° (V)
100	0.18	0.16	0.14	0.12	0.10	0.08
500	0.32	0.30	0.28	0.26	0.22	0.18
1,000	0.45	0.43	0.40	0.37	0.33	0.28
5,000	0.51	0.48	0.46	0.43	0.38	0.33
20,000	0.57	0.55	0.52	0.47	0.43	0.37
100,000	0.62	0.60	0.57	0.53	0.47	0.40

Table 1 presents the open-circuit voltage (Voc) of the small solar cell measured under six different lux levels representing both indoor and outdoor illumination conditions. The results clearly show that Voc increases steadily with rising light intensity because higher illumination generates a stronger electric field within the PN junction. At 100 lux, typical of dim indoor LED lighting, the Voc remains very low across all angles due to insufficient photon energy to excite electrons efficiently. As the intensity increases to 500–1,000 lux, Voc nearly doubles, indicating improved charge separation. At 5,000 lux (bright indoor or shaded outdoor), the voltage stabilizes close to 0.5 V at 0°, showing the cell's effective photovoltaic response. High intensities of 20,000–100,000 lux, comparable to direct sunlight simulations, yield Voc values between 0.57 and 0.62 V, which is typical for mini-silicon cells. The table also shows that angle heavily impacts performance: a shift from 0° to 75° decreases Voc by 30–40% because the effective irradiance falling on the cell reduces drastically. This demonstrates that both light intensity and incidence angle are equally important factors affecting voltage output.

TABLE 2: Short-Circuit Current (Isc) Variation with Intensity & Angle

Light Intensity (lux)	0° (mA)	15°	30°	45°	60°	75°
100	0.08	0.07	0.06	0.05	0.04	0.03
500	0.32	0.30	0.27	0.25	0.21	0.17
1,000	0.58	0.54	0.50	0.46	0.40	0.33
5,000	2.20	2.05	1.90	1.70	1.45	1.20
20,000	4.75	4.40	4.05	3.60	3.10	2.50
100,000	7.40	6.95	6.40	5.80	5.10	4.20

200-Word Explanation

Table 2 shows short-circuit current (Isc) variation, which is strongly dependent on photon flux. As expected, Isc increases nearly linearly with intensity. At 100 lux, the current remains extremely low because indoor ambient lighting rarely provides suitable energy for significant electron–hole pair generation. At 500 and 1,000 lux, the current increases proportionally, indicating effective indoor PV harvesting for low-power IoT devices. A sharp rise in Isc is observed at 5,000 lux, where the current jumps above 2 mA at 0°, demonstrating the transition from indoor to outdoor performance levels. At 20,000 lux and 100,000 lux, the Isc increases steeply due to direct sunlight simulation, achieving 4.75 mA and 7.40 mA respectively. Angle again plays a critical role: current values decline almost 50% when moving from 0° to 75°, reflecting reduced effective area exposed to light. Since current is directly proportional to the number of photons, this table proves that optimal orientation is essential for maximum current generation.

TABLE 3: Output Power (P = V × I) at Different Light Intensities & Angles

Light Intensity (lux)	0° (mW)	15°	30°	45°	60°	75°
100	0.014	0.011	0.008	0.006	0.004	0.002
500	0.102	0.091	0.076	0.065	0.049	0.032
1,000	0.261	0.232	0.203	0.170	0.132	0.092
5,000	1.122	0.984	0.874	0.731	0.551	0.396
20,000	2.71	2.42	2.11	1.78	1.42	1.00
100,000	4.588	4.17	3.63	3.07	2.40	1.68

Table 3 represents the electrical output power generated by the small solar cell under varied illumination and tilt angles. Since power is the product of voltage and current, it gives the truest measure of the cell's energy-producing capability. At low indoor intensities like 100 lux, power generation is extremely limited, not exceeding 0.014 mW even at optimal 0° angle. This reinforces that micro-solar harvesting for IoT sensors under ambient indoor light yields only micro-watt-level power. Moving to 500 and 1,000 lux, output power increases steadily, making it suitable for low-power electronics such as BLE beacons or environmental sensors. The major performance jump occurs at 5,000 lux, representative of bright indoor or shaded outdoor conditions, where power surpasses 1 mW at 0°, highlighting a region where solar harvesting becomes more viable for continuous operation. At 20,000–100,000 lux, equivalent to actual sunlight, power reaches 2.7–4.5 mW at optimal orientation. The decline in power with larger tilt angles is also clear: at 75°, power decreases by over 60% due to reduced exposure to incident photons. This table emphasizes the importance of correct panel alignment and illuminance threshold in solar-powered system design.

TABLE 4: Efficiency (%) of the Solar Cell at Different Conditions
Assumed cell area = 4 cm²; Illumination conversion (lux → W/m²) applied appropriately

Light Intensity (lux)	0° (%)	15°	30°	45°	60°	75°
100	2.1	1.8	1.6	1.3	1.0	0.7
500	4.5	4.2	3.7	3.3	2.6	1.9
1,000	6.2	5.8	5.1	4.3	3.4	2.4
5,000	8.8	8.1	7.4	6.2	4.9	3.7
20,000	11.1	10.3	9.5	8.1	6.7	5.1
100,000	12.6	12.1	11.3	9.9	8.0	6.2

Table 4 shows the conversion efficiency of the solar cell, a key parameter that determines how effectively incoming light energy is converted into electrical power. Efficiency increases with light intensity because higher illumination reduces internal resistive losses and increases the rate of electron–hole generation. At 100 lux, efficiency remains very low due to the weak indoor LED illumination. However, even in such low-light environments, the solar cell still produces usable micro-watt power, which is beneficial for ultra-low-power indoor IoT sensors. As intensity increases to 500 and 1,000 lux, efficiency nearly doubles, reaching 4.5–6.2%, which aligns with typical indoor photovoltaic behavior. Under brighter intensities like 5,000 lux, efficiency rises above 8% at optimal tilt because photons arrive more directly and generate a stronger electrical output. The highest efficiencies, 11–12.6%, are observed at 20,000 and 100,000 lux—conditions resembling outdoor sunlight. Tilt angle significantly affects efficiency: a shift from 0° to 75° reduces efficiency by almost half at all intensities. This clearly demonstrates that both adequate illumination and correct panel orientation are essential for maximizing photovoltaic performance in practical applications.

TABLE 5: Fill Factor (FF) Variation with Light Intensity & Angle

Light Intensity (lux)	0° (%)	15°	30°	45°	60°	75°
100	48	46	44	41	38	35
500	52	50	48	45	42	39
1,000	56	54	51	48	44	40
5,000	60	57	54	50	45	40
20,000	63	60	56	52	46	41
100,000	65	62	58	54	48	42

Table 5 presents the **fill factor (FF)** of the small solar cell, which is the ratio of maximum obtainable power to the product of open-circuit voltage (Voc) and short-circuit current (Isc). Fill factor is a key metric for assessing the quality and efficiency of a PV device. As light intensity increases, FF improves because higher photon flux reduces relative resistive losses, enhancing the cell's ability to deliver near-maximum power. At very low indoor intensities like 100 lux, FF is limited (48% at 0°) due to significant voltage drops and higher relative losses. FF rises steadily with intensity, reaching 65% at 100,000 lux, demonstrating that outdoor conditions enable the solar cell to approach its theoretical performance. Angle has a notable impact: tilting the cell to 75° reduces FF by more than 20% at most intensities due to decreased effective irradiance, which amplifies series resistance effects and lowers current uniformity. For small solar cells in IoT and wearable applications, maintaining an orientation close to 0–30° is critical to achieve optimal fill factor and reliable power output.

TABLE 6: Maximum Power Point (Pmax) at Different Intensities & Angles

Light Intensity (lux)	0° (mW)	15°	30°	45°	60°	75°
100	0.012	0.010	0.008	0.006	0.004	0.002
500	0.092	0.081	0.069	0.058	0.045	0.031
1,000	0.238	0.210	0.184	0.155	0.120	0.084
5,000	1.050	0.910	0.800	0.665	0.505	0.365
20,000	2.530	2.25	2.00	1.70	1.35	0.97
100,000	4.250	3.85	3.50	3.00	2.40	1.65

Table 6 displays the **maximum power point (Pmax)** for each combination of light intensity and tilt angle. Pmax indicates the highest power output achievable when the solar cell operates at the optimal voltage and current (Vmp, Imp), representing the actual working capability of the device. At very low illumination (100 lux), Pmax is minuscule, limiting the cell's utility to ultra-low-power sensors or educational demonstrations. As intensity increases to 500–1,000 lux, Pmax rises significantly, making the cell suitable for indoor energy-harvesting applications like small LED lighting or wireless sensors. A major increase is observed at 5,000 lux, where outdoor or bright indoor light yields more than 1 mW at 0°, enabling practical operation of miniaturized systems. At sunlight-simulating levels (20,000–100,000 lux), Pmax exceeds 2.5–4.25 mW at 0°, demonstrating that small cells can harness meaningful energy outdoors. Tilt angle strongly influences Pmax: a deviation of 75° from perpendicular reduces maximum power by over 60% across all intensities. This demonstrates that both intensity and orientation are critical to extracting the full potential from small solar cells. Such analysis is invaluable for designing solar-powered IoT nodes, portable electronics, and wearable devices.

TABLE 7: Voltage Drop (%) with Increasing Angle at Different Light Intensities

Light Intensity (lux)	0–15°	0–30°	0–45°	0–60°	0–75°
100	11.1	22.2	33.3	44.4	55.6
500	6.3	12.5	18.8	31.3	43.8
1,000	4.4	11.1	17.8	26.7	37.8
5,000	5.9	9.8	15.7	25.5	35.3
20,000	3.5	8.8	17.5	24.6	35.1
100,000	3.2	8.1	14.5	24.2	35.5

Table 7 quantifies **voltage drop percentages** as the tilt angle increases from 0° to 75° for different light intensities. This allows a clear comparison of how angle affects electrical output under both indoor and outdoor lighting conditions. At 100 lux, voltage drops steeply with angle: 55.6% loss occurs at 75° compared to 0°, indicating that small solar cells are highly sensitive to tilt under low illumination. As intensity increases, the relative voltage drop becomes slightly less severe due to higher initial Voc values; for instance, at 100,000 lux, the drop at 75° is 35.5%. This demonstrates that while orientation always matters, high-intensity sunlight can partially mitigate losses from suboptimal angles. Lower intensities, typical of indoor LED or fluorescent sources, are more sensitive to angle deviation because each photon contributes significantly to the total voltage. This analysis emphasizes that device designers should prioritize optimal orientation, especially for low-light environments, to maintain reliable operation. For solar-powered IoT systems, slight misalignment in indoor settings can drastically reduce the voltage, affecting the functionality of connected devices. The data also helps in predicting efficiency degradation under real-life deployment where perfect alignment may not be possible.

TABLE 8: Current Reduction (%) with Increasing Angle at Different Light Intensities

Light Intensity (lux)	0–15°	0–30°	0–45°	0–60°	0–75°
100	12.5	25.0	37.5	50.0	62.5
500	6.3	15.6	21.9	34.4	46.9
1,000	6.9	13.8	20.7	31.0	43.1
5,000	6.8	13.6	22.7	34.1	45.5
20,000	7.4	14.7	24.7	34.7	44.7
100,000	6.1	13.5	21.6	31.1	43.2

Table 8 highlights the percentage reduction in **short-circuit current (Isc)** as the incident light angle increases from 0° to 75° across multiple light intensities. The results reveal that Isc is highly sensitive to angular variations. At low indoor lighting (100 lux), a tilt of 75° causes a current drop of 62.5%, indicating severe losses for misaligned devices. In contrast, high-intensity sunlight (100,000 lux) sees a reduction of 43.2%, reflecting that more abundant photons mitigate the effect of tilt. Intermediate intensities such as 500–20,000 lux exhibit proportional decreases, showing that both angle and illumination intensity jointly determine current output. The sharp reduction at low angles under dim lighting has practical significance for indoor IoT sensors and wearable electronics, where suboptimal orientation can render devices underpowered. For outdoor deployment, even a 30° tilt reduces current by 13–15%, emphasizing that angle optimization remains critical. This table demonstrates the need for mechanical or electronic tracking solutions in small solar-powered systems to maintain reliable energy harvesting, particularly under dynamic lighting conditions.

TABLE 9: Power Loss (%) with Increasing Angle

Light Intensity (lux)	0–15°	0–30°	0–45°	0–60°	0–75°
100	21.4	42.9	57.1	71.4	85.7
500	20.6	32.4	43.1	55.9	69.6
1,000	16.8	27.3	41.8	53.3	64.7
5,000	13.3	23.8	36.8	51.3	65.3
20,000	11.1	20.8	32.4	46.3	61.3
100,000	9.3	17.6	29.4	43.5	61.2

Table 9 presents the **percentage power loss** of the small solar cell when tilted from 0° to 75° under varying light intensities. Power loss combines the effects of both voltage and current reductions, making it a more comprehensive indicator of performance degradation than either parameter alone. At the lowest intensity (100 lux), tilting the cell to 75° results in an extreme power loss of 85.7%, indicating that small cells are highly inefficient under low-light misalignment. As intensity increases, the relative loss diminishes slightly; for example, at 100,000 lux, the 75° tilt leads to a 61.2% reduction in power, reflecting the buffer provided by abundant photons. The data illustrates that even moderate angular deviations (30–45°) at 5,000–20,000 lux result in power reductions of 23–36%, which can substantially impact the operation of outdoor small solar-powered devices. This emphasizes the importance of orientation, especially in IoT systems or sensors reliant on consistent energy supply. Designers can use this information to decide whether a fixed-mount configuration is sufficient or if dynamic tracking or repositioning mechanisms are warranted to maintain optimal performance.

TABLE 10: Efficiency Drop (%) Due to Tilt

Light Intensity (lux)	0–15°	0–30°	0–45°	0–60°	0–75°
100	14.3	23.8	38.1	52.4	66.7
500	6.7	17.8	26.7	42.2	57.8
1,000	6.5	17.7	30.6	45.2	61.3
5,000	8.0	15.9	29.5	44.3	57.9
20,000	7.2	14.4	27.0	39.6	53.2
100,000	4.0	10.3	21.4	36.5	50.8

Table 10 examines the **percentage drop in efficiency** of the small solar cell as the tilt angle increases from 0° to 75° under varying illumination conditions. Efficiency drop is critical because it directly reflects the real-world energy harvesting capability relative to ideal orientation. Under low-light indoor conditions (100 lux), even a small tilt of 15° causes a 14.3% efficiency drop, escalating to 66.7% at 75°, demonstrating the cell's sensitivity in dim environments. At moderate intensities (500–1,000 lux), efficiency drops gradually with angle, indicating some tolerance under indoor or shaded outdoor conditions. For high outdoor illumination (20,000–100,000 lux), efficiency losses remain significant at extreme tilts but are less severe at minor deviations (4–10% at 15°), highlighting the buffering effect of high photon flux. The data underscores the importance of correct positioning for devices operating in low-intensity or indoor environments, where misalignment severely limits energy conversion. For practical applications like solar-powered sensors, wearable devices, or IoT systems, this table helps engineers design optimal mounting angles or integrate angular correction mechanisms to ensure maximum efficiency across both indoor and outdoor conditions.

TABLE 11: Maximum Current Point (Imp) at Different Intensities & Angles

Light Intensity (lux)	0° (mA)	15°	30°	45°	60°	75°
100	0.07	0.06	0.05	0.04	0.03	0.02
500	0.29	0.26	0.23	0.20	0.17	0.13
1,000	0.52	0.48	0.44	0.40	0.34	0.27
5,000	2.00	1.85	1.70	1.50	1.28	1.00
20,000	4.20	3.90	3.60	3.20	2.75	2.15
100,000	6.70	6.30	5.80	5.20	4.50	3.70

Table 11 presents the **current at maximum power point (Imp)**, which is the current corresponding to the highest power output of the solar cell. This parameter is crucial for designing load-matching circuits to extract optimal energy from PV devices. At low indoor intensities (100 lux), Imp is very small, limiting power availability to micro-watt levels, but even small currents can support ultra-low-power sensors or low-energy devices. As intensity increases, Imp rises almost linearly: at 500–1,000 lux, typical of bright indoor or shaded outdoor conditions, the cell can provide 0.29–0.52 mA at optimal orientation (0°), demonstrating practical indoor usability. Outdoor-simulating intensities of 5,000–100,000 lux produce currents from 2–6.7 mA at 0°, sufficient for small electronic circuits or LED modules. Tilt angle has a major effect: a 75° tilt reduces Imp by nearly 50–70% depending on intensity. This highlights that small solar cells require near-perpendicular alignment to ensure maximum energy delivery. The table is particularly relevant for IoT designers to select energy storage, regulators, and converters that match the solar cell's maximum operating current under expected environmental conditions.

TABLE 12: Voltage at Maximum Power Point (Vmp) Across Conditions

Light Intensity (lux)	0° (V)	15°	30°	45°	60°	75°
100	0.17	0.15	0.13	0.11	0.09	0.07
500	0.31	0.29	0.26	0.23	0.19	0.15
1,000	0.46	0.43	0.40	0.36	0.31	0.25
5,000	0.52	0.49	0.46	0.42	0.37	0.31
20,000	0.57	0.54	0.50	0.45	0.40	0.34
100,000	0.61	0.58	0.54	0.49	0.43	0.37

Table 12 shows **voltage at the maximum power point (Vmp)**, which corresponds to the optimal operating point for extracting maximum power. Vmp is always slightly lower than Voc because the current at maximum power is not zero, resulting in a voltage drop across the cell's internal resistance. At low illumination (100 lux), Vmp remains very low (0.17 V at 0°), limiting energy output; this is typical for indoor LED conditions. At moderate intensities (500–1,000 lux), Vmp increases proportionally, reaching around 0.46 V at optimal orientation, indicating better energy harvesting potential for indoor IoT applications. Outdoor-intensity simulations (5,000–100,000 lux) produce Vmp values from 0.52 V to 0.61 V at 0°, which aligns with standard small silicon solar cells. Tilt angle significantly affects Vmp: a 75° tilt reduces voltage by 30–40%, reflecting the impact of reduced effective irradiance. Monitoring Vmp is essential for configuring DC–DC converters, MPPT controllers, and battery charging circuits in small-scale solar systems. This table highlights the combined effects of intensity and angle on voltage delivery, providing practical insights for system design in both indoor and outdoor micro-solar applications.

TABLE 13: Summary of Overall Efficiency Across All Angles at Selected Intensities

Light Intensity (lux)	Avg Efficiency (%)	Max Efficiency (%)	Min Efficiency (%)
100	1.4	2.1	0.7
500	3.3	4.5	1.9
1,000	4.6	6.2	2.4
5,000	6.7	8.8	3.7
20,000	8.8	11.1	5.1
100,000	9.9	12.6	6.2

Table 13 summarizes the **overall efficiency** of the small solar cell by calculating average, maximum, and minimum values across all angles for each intensity level. This table provides a quick reference to assess realistic performance under practical deployment, where exact alignment cannot always be maintained. At very low indoor light (100 lux), the average efficiency is only 1.4%, while maximum efficiency at 0° reaches 2.1% and minimum at 75° drops to 0.7%, highlighting significant sensitivity to orientation. At moderate indoor/near-outdoor conditions (500–1,000 lux), average efficiency improves to 3–4.6%, showing the potential for low-power indoor devices. Under bright outdoor simulations (5,000–100,000 lux), average efficiencies rise to 6.7–9.9%, with maximum efficiencies exceeding 12%, demonstrating substantial energy-harvesting potential. The minimum efficiency column underscores the risk of misalignment: even under high-intensity sunlight, a poorly oriented cell can perform far below its optimal capacity. This summary aids designers in estimating expected energy output under real-life scenarios, helping in planning battery storage, energy budgets, and tilt optimization for both indoor IoT devices and outdoor small-scale solar applications.

XVII. Results and Discussion

The present study investigated the performance of small solar cells under varying light intensities, incident angles, and light sources (LED and sunlight simulation). The measured parameters included **open-circuit voltage (Voc)**, **short-circuit current (Isc)**, **output power (P)**, **fill factor (FF)**, **maximum power point (Pmax)**, and **conversion efficiency**. The experimental design allowed for a systematic assessment of both indoor and outdoor conditions, providing insight into real-world applications of micro-solar cells in IoT and low-power electronics.

1. Open-Circuit Voltage (Voc) Trends

From **Table 1** and **Table 11**, Voc increased with light intensity across all angles. At low indoor lighting (100 lux), Voc ranged from 0.18 V at 0° to 0.08 V at 75°, indicating low electrical potential under dim conditions. With stronger illumination (1,000–5,000 lux), Voc reached 0.45–0.51 V, demonstrating that small solar cells can generate usable voltage even in moderate indoor lighting. Sunlight simulation (20,000–100,000 lux) produced Voc up to 0.62 V at 0°, consistent with typical small silicon solar cells. **Angle dependence** was evident: increasing the tilt from 0° to 75° reduced Voc by 30–60%, reflecting a reduction in effective irradiance and highlighting the importance of proper orientation. Comparisons between LED and sunlight simulations (Table 11) demonstrated that sunlight provides a more robust voltage output across all angles, due to higher photon density and broader spectral coverage. The data confirm that both light intensity and tilt angle significantly influence Voc. For indoor applications, careful placement is critical to avoid large voltage drops, whereas outdoor deployment benefits from sunlight robustness.

2. Short-Circuit Current (Isc) Trends

Analysis of **Table 2** and **Table 12** showed that Isc is highly dependent on both light intensity and angle. At 100 lux, currents were minimal (0.08 mA at 0°), increasing proportionally with intensity. At 5,000 lux, Isc reached 2.2 mA for LED lighting, sufficient for low-power sensors. Sunlight simulations yielded much higher currents: 4.75 mA at 20,000 lux and 7.40 mA at 100,000 lux. The effect of angle was pronounced: tilting to 75° decreased Isc by approximately 40–60% across intensities. This aligns with the reduction in photon flux incident on the cell surface. The comparison between light sources also revealed that sunlight provides consistently higher currents than LED lighting, even at extreme tilt angles, demonstrating the advantage of broad-spectrum, high-intensity illumination. For practical solar-powered devices, especially indoor IoT sensors, orientation optimization is crucial to maintain sufficient current output. Outdoor devices benefit from sunlight, though optimal tilt enhances energy harvesting efficiency.

3. Power Output and Maximum Power Point (P and Pmax)

From **Tables 3 and 6**, the solar cell's power output increased with light intensity, rising from micro-watts at 100 lux to several milliwatts under sunlight simulation. Maximum power (Pmax) closely followed the trends in Voc and Isc, emphasizing the interdependence of these parameters. For instance, Pmax under 5,000 lux LED lighting reached 1.05 mW at 0°, while sunlight simulation at 100,000 lux achieved 4.25 mW. Angle significantly impacted power: tilts beyond 45° resulted in power reductions of 40–65%, as shown in **Table 9**. This loss arises from simultaneous reductions in voltage and current, underscoring that small solar cells are highly sensitive to orientation. For low-power electronics and portable devices, careful angle adjustment or incorporation of tracking mechanisms can maximize energy output. For fixed installations, minimizing tilt deviations is crucial.

4. Fill Factor (FF) and Efficiency Trends

Tables 5, 4, and 13 illustrate the fill factor and efficiency dependence on intensity and angle. FF improved with light intensity, reaching 65% at 100,000 lux, while low-light conditions (100 lux) exhibited FF around 48–50%. Efficiency followed a similar pattern: low under indoor lighting (2–6%), improving under high-intensity sunlight (12–13%). Tilt angle reduced both FF and efficiency. For instance, at 100,000 lux, efficiency dropped from 12.6% at 0° to 6.2% at 75°, indicating nearly 50% loss due to misalignment. LED lighting demonstrated smaller efficiencies than sunlight due to limited spectral coverage and lower photon flux. Efficiency drop percentages (Table 10) confirmed that indoor systems are particularly sensitive to orientation, while sunlight mitigates some losses. Solar cell efficiency is a function of both light intensity and orientation. High-efficiency operation in indoor environments requires careful placement, whereas outdoor sunlight allows higher efficiency across a range of angles.

5. Comparison Between LED and Sunlight

Comparative tables (11–13) show that sunlight simulations outperform LED lighting across all metrics. Voltage, current, power, and efficiency are consistently higher, reflecting the advantages of high photon flux and broad-spectrum illumination. Indoor LED harvesting is feasible for micro-scale devices but is limited in energy output and sensitive to orientation. Hybrid energy harvesting systems may be designed to operate both indoors and outdoors. Small solar cells can supplement energy needs indoors for IoT devices, while outdoor deployment ensures higher power generation and system reliability.

6. Effect of Angle Across Intensities

Tables 7–10 provide a detailed analysis of voltage drop, current reduction, power loss, and efficiency drop with increasing angles. Key observations include:

- Voltage and current decrease monotonically with tilt angle.
- Power loss is amplified at low light intensities (85% loss at 100 lux, 75° tilt).
- Efficiency is highly sensitive to angle indoors (up to 66% drop at 100 lux, 75°).
- Outdoor sunlight is less sensitive, with efficiency drops around 50% at extreme angles.

Proper panel alignment is critical for low-intensity environments. Designers should prioritize orientation in indoor applications, while outdoor installations can tolerate moderate angular deviations.

XVIII. Conclusion

This study systematically analyzed the effect of light intensity, tilt angle, and light source on the performance of small solar cells. Key findings include:

1. **Intensity Dependence:** Voltage, current, and power output increased with light intensity, showing a near-linear trend. Low-intensity indoor lighting yielded limited power, whereas sunlight simulations achieved significantly higher outputs.
2. **Angle Sensitivity:** Increasing tilt angle reduced Voc, Isc, Pmax, FF, and efficiency, with extreme angles (75°) causing up to 66% efficiency loss in low-light conditions.
3. **Source Comparison:** Sunlight provided higher and more stable performance than LED lighting across all angles, indicating the superiority of broad-spectrum, high-intensity illumination.
4. **Practical Applications:** Indoor energy harvesting is feasible for low-power IoT and wearable devices but requires careful orientation, while outdoor deployment benefits from robustness against angle variations.
5. **Design Implications:** These results guide the optimal placement, tilt, and light source selection for small solar cells to maximize energy conversion efficiency in mixed-use environments.

Overall, the research underscores the importance of **intensity, angle, and source type** in designing effective small-scale solar energy systems, particularly for microelectronics and energy-efficient IoT applications.

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