

Article

LED-Based Low-Cost Educational Platform for Simulating Photovoltaic Systems

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Abstract

Studying photovoltaics in engineering and science curricula is a time-consuming and expensive activity. This is why simulations are used, which, however, do not allow direct observation of the physical phenomena occurring in the devices. Based on an array of LEDs (light-emitting diodes) in photodetection mode, a low-cost educational platform for simulating photovoltaic systems including bypass and blocking diodes was developed. This allowed for the experimental characterization of the system's I-V and P-V characteristics, obtained with a variable-load method under controlled lighting, as well as the qualitative reproduction of key photovoltaic phenomena such as mismatch and bypass diode activation. Additionally, the system allows for quantitative analyses starting from a reference value of 25 μ W, obtained under full illumination conditions. This value will inevitably decrease as the platform's operating conditions worsen, intentionally generated to study the behavior of the platform. Although the method does not provide a representation of the real photovoltaic field, it provides a simple and low-cost tool for the experimental study of photovoltaic behavior. The paper has been conceived for educational purposes, oriented towards laboratory teaching activities.

Keywords: LED; solar panel; photovoltaic field; educational tool

1. Introduction

In the context of university science education, the use of simulators has taken on an increasingly important role thanks to their ability to represent complex phenomena, reduce laboratory costs, and provide a controlled environment. However, experience in experimental teaching shows that real experiments—even very simple ones—have an irreplaceable educational value, particularly in the early years of a university program.

Real experiments provide students with direct engagement with the behavior of the physical world. This immediate interaction:

- Fosters the development of physical intuition;
- Strengthens conceptual understanding of phenomena;
- Enables students to discern the distinction between theoretical models and experimental reality.

Although often highly sophisticated, simulators generate data that are preprocessed and lack the intrinsic irregularities characteristic of real measurements. As a consequence,



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they may inadvertently convey an oversimplified view of the complexity inherent in experimental practice.

The ability to manage uncertainty is a fundamental component in the education of scientific and technical professionals. In real laboratory settings, students:

- Measure uncertainty directly;
- Assess the repeatability of results;
- Interpret deviations and anomalies;
- Develop an understanding of instrumental limitations and their implications.

In contrast, simulators typically implement error as an artificially defined parameter rather than as the outcome of a genuine physical process. This limits the student's opportunity to cultivate a critical and reflective approach to data analysis.

Moreover, real experiments require practical competencies that cannot be replicated in a virtual environment, including:

- Assembling and configuring experimental apparatus;
- Selecting appropriate measurement ranges;
- Calibrating instruments;
- Managing sensors, cabling, power supplies, and alignment procedures.

These skills constitute an essential professional asset for students intending to pursue careers in experimental research, industry, or technological development [1–6].

Photovoltaics has not been formally taught in traditional engineering and science disciplines [7–10]. However, in recent years, the integration of renewable energy sources has led to a restructuring of traditional engineering and science curricula [11]. In particular, teaching photovoltaic (PV) technology requires students to understand highly nonlinear concepts, such as current-voltage (I-V) characteristics, maximum power point tracking (MPPT), and the complex behavior of bypass diodes under partial shading conditions [12].

Furthermore, to experiment with PV cells in the laboratory is a time-consuming and costly task. Thus, effectively conveying these concepts in a university laboratory presents significant pedagogical and logistical challenges.

So, to overcome this problem of studying the behavior of photovoltaic cells under different operating conditions, digital simulation techniques are used, such as MATLAB/Simulink, PSpice or software dedicated to photovoltaics [13–15]. There is a large number of different simulation software available [16–18]. PSpice has been used for the study of silicon solar cells and modules constructed from such series-connected cell-strings [19,20]. The simple study carried out leads to valuable information that is useful in the design of PV modules and power supply systems utilizing such PV modules as their basic energy source [21].

The most important component that affects the accuracy of a simulation is the PV cell modeling. In real solar cells, the recombination represents a substantial loss, especially at low voltages or low insolation. This cannot be adequately modeled using a single-diode model. For improved accuracy, the two-diode model was proposed [22–24].

The performance of a PV array is affected by temperature, solar insolation, shading and array configuration. Under PSCs, the PV characteristics get more complex with multiple peaks [25]. Hence, it is important to understand and predict them to extract the maximum possible power.

Although simulations offer predictive estimates for modeling and characterizing photovoltaic cells, they have inherent limitations due to the temporal discretization of meteorological data and the simplification of thermal transport phenomena [26]. Furthermore, computational models cannot perfectly replicate nonlinear mismatch losses, cell soiling, and inverter thermal derating dynamics [27,28].

Furthermore, in an educational context, they do not allow direct observation of the physical phenomena occurring in photovoltaic devices. In the educational field, experimental validation is essential to understand real-world effects, such as thermal gradients, partial shading, non-ideal component properties, and environmental variability, which are often simplified or overlooked in computational models [29].

Finally, although computationally powerful and risk-free, virtual simulation does not reproduce physical reality; it insulates students from real-world experimental errors, measurement uncertainties, and hardware troubleshooting skills, which are crucial to professional engineering practice [30]. Therefore, it is necessary to combine simulations with experimental model validation.

The second approach involves the use of real outdoor PV fields or high-end indoor solar simulators equipped with xenon or halogen lamps. Despite being highly realistic, this methodology is very expensive for school settings, requires intensive maintenance, and introduces safety risks due to the high DC voltages and intense thermal/UV emission of the lamps [31,32].

To address these limitations, recent educational research has focused on the development of low-cost hardware emulators or virtual reality (VR) platforms [33,34], which, however, fail to provide tactile interaction with instruments and systems [35,36].

Therefore, there is a need for a new educational tool that can bridge the gap between mathematical simulation and expensive and dangerous real-world testing.

This research is motivated by the need to make practical laboratory training in photovoltaics accessible.

This paper proposes an innovative platform using low-cost light-emitting diodes (LEDs) operating in photodetection mode, introducing a secure, highly interactive, and low-cost hardware simulator.

The significance of this research lies in its unique ability to allow students to visually and physically interact with optical phenomena, such as casting a real shadow on a specific “cell” with their hands, and to instantly observe the nonlinear electrical consequences, including multi-peak power curves and bypass diode conduction. This provides a pedagogical bridge that fosters physical intuition and diagnostic skills in future engineers.

Finally, the aim of this article is to develop an economical and educational system that allows the laboratory simulation of a photovoltaic field through a controllable system [37,38] that uses LEDs as both a light source and photodetectors [39], allowing direct interaction with physical phenomena and verifying the correlation between theoretical models and the real behavior of photovoltaic systems [40].

The device presents the possibility of carrying out quantitative analyses, although this is limited by its hardware physicality. In fact, starting from a situation of full lighting of the platform, there is a reference of maximum power generated (25 μ W) which decreases, introducing a whole series of problems found in a real photovoltaic field and emulated with simple precautions. For example, if shading is produced by partially covering the LEDs, the reduction in power supplied can be studied quantitatively in relation to the percentage of darkened LEDs measuring voltage and current values generated from the platform.

The remainder of the article is organized as follows. Section 2 presents the fundamentals of photovoltaic cells and arrays, including the mathematical model, the I–V characteristics, and the corresponding P–V curves. Section 3 describes the LED-based matrix developed in this work. Section 4 presents the analysis of the experimental I–V curve obtained with the developed device. Section 5 discusses the experimental results. Finally, the conclusions are provided.

2. Structure of a Photovoltaic Field

Photovoltaic cells exploit the photovoltaic effect in p-n junction semiconductors. When the junction is struck by photons with energy equal to or greater than the bandgap of the semiconductor material, valence band electrons are promoted to the conduction band, generating electron–hole pairs [41].

The electric field present in the depletion region separates these charge carriers, inducing a photogenerated current that can be collected at the device terminals.

In this section, the mathematical model and the role of bypass and blocking diodes are analyzed.

2.1. Mathematical Model

Mathematical models of a photovoltaic cell are an important tool for evaluating the energy performance of photovoltaic fields under varying operating conditions, such as temperature and irradiance, as well as for the correct sizing of associated electronic converter systems.

Several usable models have been proposed in the literature. Their performance, in terms of accuracy, required computational power, and ease of parameter determination, must be assessed based on the intended application.

To describe the electrical behavior of photovoltaic cells, ideal models include a single-diode model (5 parameters), a dual-diode model (7 parameters), simplified empirical models, and numerical models based on experimental parameters [42–44].

Among these, the single-diode model represents the best compromise between accuracy and computational complexity and is the most widely used in engineering applications [24,45]. Indeed, photovoltaic panel datasheets provide the five parameters required by the single-diode model; therefore, estimating these parameters is more time-efficient than estimating the seven parameters required by the dual-diode model. Furthermore, as shown in Figure 1, the dual-diode model exhibits a more pronounced current drop and a lower open-circuit voltage than the single-diode model at 25 °C. This is because the dual-diode model takes into account recombination processes in the depletion region of the p-n junction, while the single-diode model neglects them. These processes become relevant mainly under low-irradiation conditions.

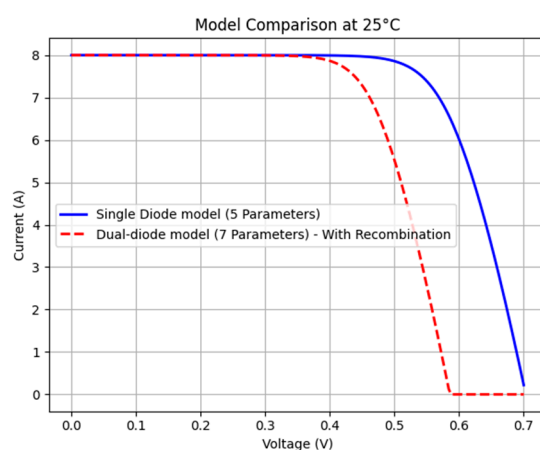


Figure 1. Single-diode model and dual-diode model comparison at 25 °C.

This paper considers the single-diode model, derived from the Shockley p-n junction equation, appropriately extended to include non-ideal resistive phenomena.

The photovoltaic cell in this model is represented by an equivalent circuit that includes a photogenerated current source I_{ph} , a p-n junction equivalent diode, a series resistance R_s associated with the material losses and a shunt resistance R_p that takes into account the leakage currents [40]. In real conditions $R_s \rightarrow 0$ and $R_p \rightarrow \infty$.

The I-V characteristic of the cell is described by the implicit equation [46–48]:

$$I = I_{ph} - I_0 \left[\exp \left(\frac{V + IR_s}{nV_t} \right) - 1 \right] - \frac{V + IR_s}{R_p} \quad (1)$$

where I is the output current; V is the terminal voltage; I_{ph} is the photogenerated current; I_0 is the diode's saturation current; n is the ideality factor; and V_t is the thermal voltage, given by:

$$V_t = \frac{kT}{q} \quad (2)$$

where k is the Boltzmann constant; T is the absolute temperature; and q is the elementary charge. The exponential term describes the nonlinear behavior of the junction, while the resistances account for the device's internal losses.

The voltage-current (I-V) characteristic and corresponding power-voltage (P-V) curves are shown in Figure 2.

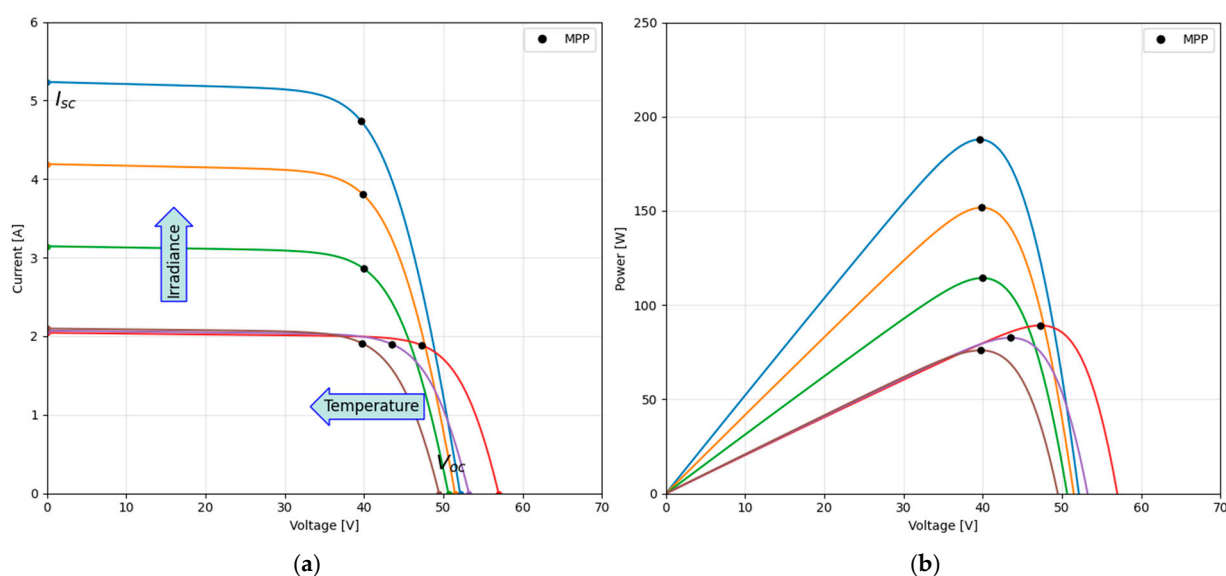


Figure 2. I-V characteristics (a) and corresponding P-V curves (b) of a photovoltaic cell under varying irradiance and temperature conditions. The maximum power points (MPPs) are indicated for each curve.

Under short-circuit conditions, the generated current is maximal, while under open-circuit conditions, the voltage is maximal.

In both conditions, the electrical power produced is zero, while, as the voltage increases, the power increases until it reaches the maximum power point. From the maximum, it then decreases rapidly until reaching the no-load voltage.

The cell's fundamental parameters are:

- I_{sc} , short-circuit current corresponding to $V = 0$;
- V_{oc} , open-circuit voltage corresponding to $I = 0$;
- MPP, maximum power point, obtained from the condition $dP/dV = 0$, which determines the device's optimal operating point.

However, photovoltaic cell performance depends heavily on environmental conditions [49]. Furthermore, to emulate realistic operating conditions it is necessary to take into account the dynamic environmental factors that determine the behavior of photovoltaic systems, i.e., environmental temperature and solar irradiance. In numerical studies, such as the one developed by [50], meteorological datasets are processed with mathematical thermal models to calculate the effective operating temperature of the PV cell (T_C) and the effective tilt irradiance (G_{eff}).

Figure 3 shows a simulation of daily irradiance, the variation in ambient and cell temperature and the power delivered. The irradiance is represented by a bell curve with the peak corresponding to the maximum temperature of the cell (50 °C) which is very different from the ambient temperature.

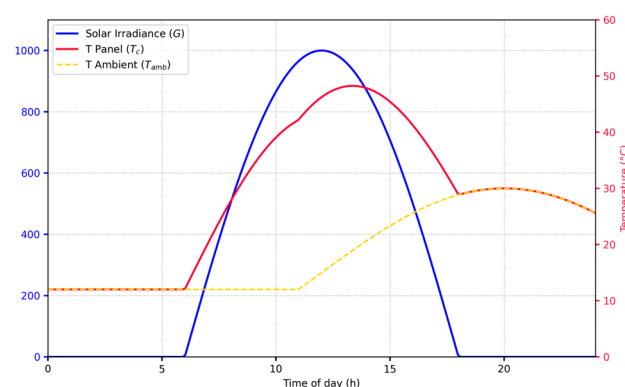


Figure 3. Simulation of solar irradiance (blue), ambient temperature (yellow) and cell temperature (red) as a function of the time of day.

The photogenerated current I_{ph} is proportional to the incident irradiance G [51]:

$$I_{ph} = [I_{sc, STC} + K_i(T - T_{STC})] \frac{G}{G_{STC}} \quad (3)$$

where G_{STC} is the irradiance in Standard Test Conditions (STC); $I_{sc, STC}$ is the short-circuit current in STC; K_i is a temperature coefficient of the short-circuit current; T is the cell operating temperature; and T_{STC} is the reference temperature under STC, equal to 298.15 K (25 °C).

In particular, increasing irradiance causes an increase in current and increasing temperature causes a reduction in open-circuit voltage and, consequently, a reduction in maximum deliverable power (Figure 2).

2.2. Extension to Modules and Fields

In real applications, cells are connected in series and parallel to form modules, which, when connected together, form strings. For N_s cells in series and N_p strings in parallel, we have:

$$V_{tot} = N_s V_{cell} \quad (4)$$

$$I_{tot} = N_p I_{string} \approx N_p I_{cell} \quad (5)$$

By inserting these parameters into the single-diode Equation (1), we obtain the model for a photovoltaic field:

$$I = N_p I_{ph} - N_p I_0 \left[\exp \left(\frac{V + I R_s \frac{N_s}{N_p}}{n N_s V_t} \right) - 1 \right] - \frac{V + I R_s \frac{N_s}{N_p}}{R_p \frac{N_s}{N_p}} \quad (6)$$

Non-uniform irradiance or temperature can induce electrical mismatch phenomena, so that a single shaded cell can limit the current of the entire string [52].

When a single cell in a module is shaded, power is drawn from the shaded cell. In principle, a bypass diode, a normally reverse-biased diode in parallel with the cell, can be used to isolate the shaded cell and provide an alternative path for current flow [53].

Furthermore, if exposed to low levels of radiation, photovoltaic cells tend to reduce their power output, affecting all other cells in series; the cell may even switch to reverse conduction (if the I exceeds the short-circuit value, the cell absorbs power instead of generating it). This can cause over-voltages and overheating at the ends of the darkened cells, because the other cells produce voltage while the darkened ones act as a load.

To prevent damage, diodes are used that allow the current to flow through the darkened cell (bypass). Ideally, one diode would be used for each cell, but, for economic reasons, one to three diodes are usually used for each module.

2.3. Role of Bypass and Blocking Diodes: Effect of Bypass Diode

In photovoltaic fields, connecting multiple modules in series and parallel makes the system sensitive to non-uniform irradiation. Indeed, in the presence of partial shading, the current of the entire string is limited by the module generating the lowest current. This causes reverse biasing of the less irradiated modules, resulting in local power dissipation and the formation of hotspots, which are responsible for device degradation [54,55].

To mitigate these effects, bypass diodes and blocking diodes are used, which perform different but complementary functions in protecting and optimizing the field [56].

Figure 4 shows the bypass diodes connected in parallel to each module while the blocking diodes are inserted in series with the strings.

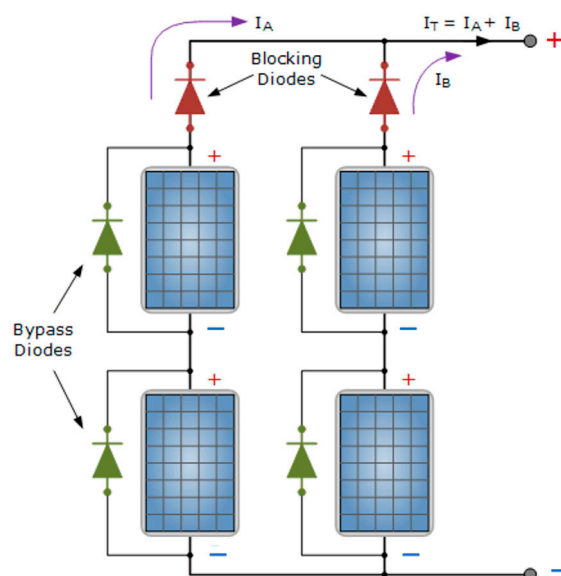


Figure 4. Diagram of a photovoltaic module system highlighting the integration of bypass and blocking diodes.

Figure 5 shows the bypass diode and shading scheme. Ideally, equal current flows through the cells in a series array. If one cell is shaded, reverse bias occurs, which acts as a load and can cause problems such as hot spots that can damage the system [57]. There are two types of shading: uniform and non-uniform [58].

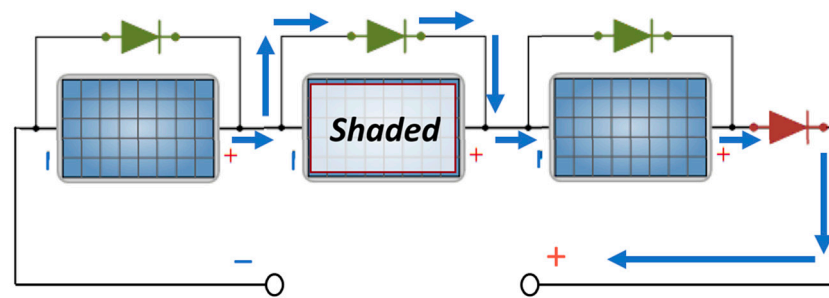


Figure 5. Equivalent circuit of a photovoltaic string with bypass diodes under partial shading conditions. The shaded cell limits the current flow, activating the bypass diode and modifying the current path. Arrows indicate the direction of current flow.

Under uniform shading (USC) conditions, all PV modules generate the same amount of current. However, the shaded cell will generate less current during partial shading (PSC) conditions [15]. The shaded module limits the overall current generation of the PV array. As a result, the solar cells become reverse-biased due to the mismatch effect and dissipate energy in the form of heat.

2.3.1. Effect of Bypass Diode

To avoid the problem of shading and prevent the formation of hot spots, the conventional solution is to install bypass diodes connected in parallel with each module, but with opposite polarity. Under normal operating conditions, each solar cell will be forward-biased, so the bypass diode will be reverse-biased and behave as an open circuit, not conducting.

However, if a solar cell is reverse-biased due to a discrepancy in the short-circuit current between several cells connected in series due to shading, for example, then the bypass diode conducts, thus allowing some of the current from the unshaded solar cells to flow into the external circuit [59].

The operating principle can be described as follows:

- Under normal conditions, $V_d < 0$, the diode is disabled;
- In the presence of reverse bias ($V_d > V_{string}$), the diode conducts and diverts the current.

The activation of the diode results in reduced heat dissipation in shaded cells, prevents hotspot formation, contributes to the preservation of the module's structural integrity, and alters the module's I-V characteristic [60].

2.3.2. Effect of Blocking Diode

The blocking diodes were connected in series with the string of series-connected PV modules in order to avoid current imbalance caused by shading. The function of the blocking diode is to prevent the reverse flow of current, particularly from the secondary power sources such as batteries or inverters during the absence of light [61].

Current in the string is therefore only allowed in the direction of generation: $I_{string} > 0$. However, for reverse voltage, the diode is cut off, with I_{rev} approximately 0.

2.3.3. Effect of Diodes on the I-V Curve

In the absence of shading, the module's I-V curve maintains a regular pattern with a single PPM. The presence of diodes modifies the electrical behavior of the photovoltaic field [53].

Figure 6 shows how these elements significantly alter the overall I-V characteristic of the PV field, introducing nonlinear regions and discontinuities in the power curve [62,63].

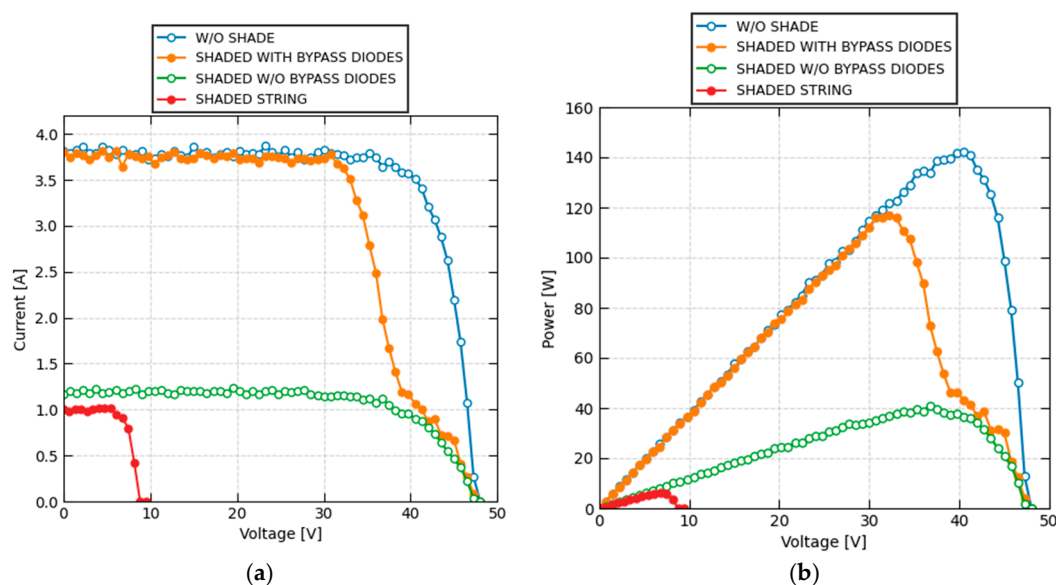


Figure 6. I-V characteristics (a) and corresponding P-V curves (b) of the photovoltaic cells under different shading conditions and bypass diode configurations [62,63].

In particular, when one or more bypass diodes become conductive, the characteristic changes, generating discontinuities [64]. From an electrical perspective, the intervention of the diode introduces a step in the overall I-V characteristic, since the voltage of the bypassed section is subtracted from the total module voltage. In the presence of multiple diodes, the field curve may have multiple inflection points and different local maxima in the power curve [60,65].

The total module voltage becomes the sum of the voltages of the individual sections protected by the bypass diodes, taking into account the state (active or disabled) of each diode:

$$V_{mod} = \sum_{i=0}^k \max(V_i(I), -V_{d,i}) \quad (7)$$

where $V_i(I)$ is the voltage generated by the i -th section of cells for a given current I and $V_{d,i}$ is the threshold voltage of the bypass diode (usually between 0.3 V and 0.7 V).

This behavior produces a power curve characterized by multiple local maxima, a particularly important aspect in maximum power point tracking (MPPT) systems, which must distinguish the global maximum from secondary maxima [66].

In contrast, blocking diodes influence the voltage available at the terminals, introducing a forward voltage drop:

$$V_{out} = V_{string} - V_{block} \quad (8)$$

where the potential drop V_{block} follows the characteristic equation of the diode:

$$V_{block} = n_d V_t \ln \left(\frac{I}{I_{s,d}} + 1 \right) + I R_d \quad (9)$$

where I is the current flowing through the string; n_d is the ideality factor of the blocking diode; $I_{s,d}$ is the diode reverse saturation current; and R_d is the internal series resistance of the diode.

The inclusion of blocking diodes introduces power dissipation that reduces the overall efficiency of the system. The power dissipated by the blocking diode is given by:

$$P_{loss,d} = V_{block} I \approx V_\gamma I + R_d I^2 \quad (10)$$

In the case of this research, this aspect is particularly relevant for comparing the behavior of the real photovoltaic field with that of the LED matrix operating in reception mode.

3. LED Matrix Structure

Studying the I-V characteristic of real photovoltaic modules subjected to controlled irradiance in an educational setting presents limitations due to cost, the need for high-power light sources, and the difficulty of reproducing partial shading.

To develop an educational device capable of simulating a photovoltaic field while overcoming these critical issues, a platform based on an array of LEDs operating in photodetection mode was developed. Although LEDs are not as efficient as photodiodes or phototransistors, their p-n junction structure allows for the generation of a measurable photocurrent when properly illuminated [67,68]. A further advantage of LEDs is their “selective” spectral response, making them sensitive to narrow wavelength ranges, enabling the development of cost-effective optical sensors [69]. Furthermore, LEDs are eco-friendly, low-cost and easy to use in educational settings for the development of efficient systems [70–72].

This allows for the creation of a physical educational model capable of representing the basic electrical phenomena in real photovoltaic systems. Indeed, the goal is not the quantitative reproduction of a photovoltaic module but rather the creation of a model that demonstrates, in a simple and repeatable way, the main phenomena observable in real photovoltaic systems. This device allows observation of the I-V curve, the load dependence, the power reduction due to shading, and the intervention of the bypass diodes and that of the blocking diodes.

The following paragraphs describe the circuit configuration adopted and the experimental methodology used to measure the system’s current-voltage characteristics.

3.1. LED as a Photodetector

The p-n junction is the basic physical structure not only of LEDs, but also of photodiodes and solar cells. In LEDs, the recombination process of electrons and holes involves the emission of photons with energies close to the bandgap energy of the semiconductor. According to Planck’s law, LEDs emit “almost” monochromatic light with photons having energies equal to [73]:

$$E_{gap} = hv = h\frac{c}{\lambda} \quad (11)$$

where h is Planck’s constant; v and λ are respectively the frequency and wavelength of the emitted radiation; and c is the speed of light.

However, an LED can function as a photodetector when illuminated by radiation of sufficient energy, generating electron–hole pairs within the junction [74]. If the device is reverse-biased, the internal electric field separates the carriers, generating a photocurrent. For this phenomenon to occur, the wavelength of the incident radiation must be:

$$\lambda = h\frac{c}{E_{gap}} \quad (12)$$

Therefore, an LED can only detect radiation with a wavelength shorter than or close to that which it would emit in direct operation [30,75].

In the device developed, green LEDs with a wavelength of 535 nm were used, illuminated by a high-intensity white LED source, to simulate solar radiation in a simplified form in a controlled environment. Figure 7 shows the spectra of the LEDs used.

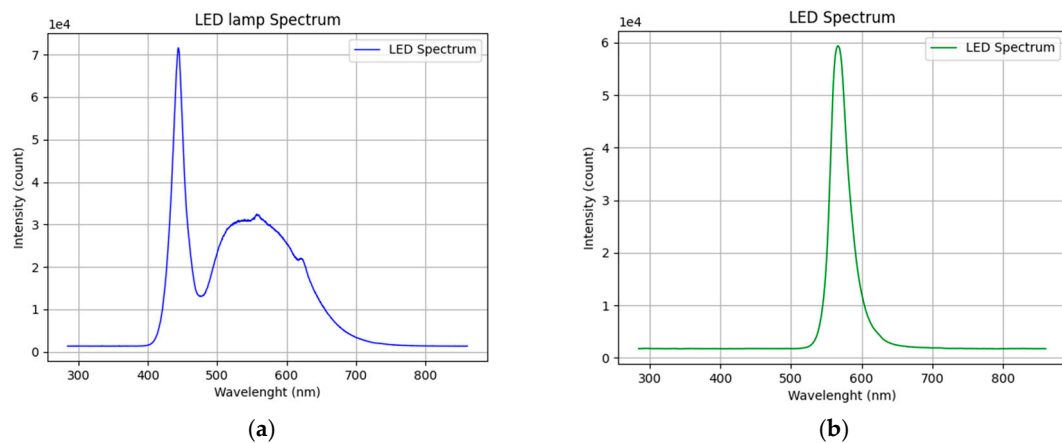


Figure 7. Emission spectra of the LEDs used in the experiment: (a) LED employed as light source; (b) LEDs used as receivers.

3.2. LED Circuit

The LED matrix designed to simulate the photovoltaic field consists of 10 parallel strings, each composed of 10 LEDs connected in series, for a total of 100 LEDs. Each LED represents a module of the photovoltaic system.

Figure 8 shows the electronic circuit of the LED matrix.

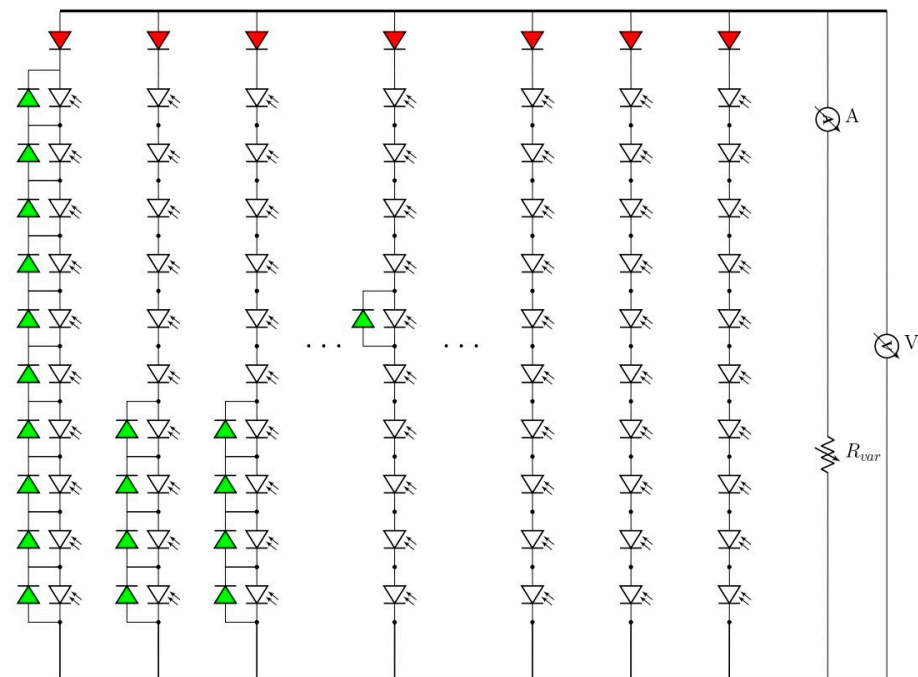


Figure 8. Schematic of the LED-based device. Bypass diodes are highlighted in green, while blocking diodes are highlighted in red.

To simulate the behavior of real photovoltaic fields, blocking diodes were inserted in series with each string to prevent reverse currents, and bypass diodes were inserted in specific areas of the matrix to simulate the system's behavior in the presence of localized shading, allowing analysis of the system's characteristic curve in different configurations.

The platform is shown in Figure 9, which highlights the LED matrix, the Laboratory Jack, the switch for variable-load measurements, and the switch for isolating the central strings of the panel.

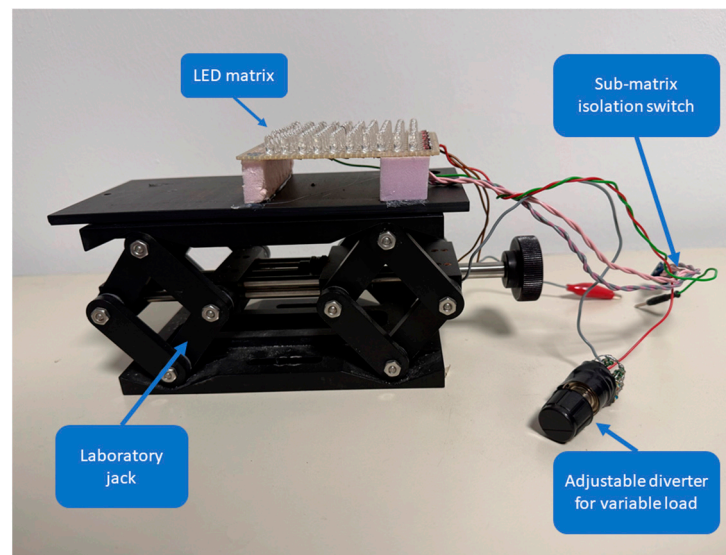


Figure 9. LED matrix setup, with Laboratory Jack, diverter and switch.

The LED matrix was placed on a Laboratory Jack so that the distance from the source could be varied, initially kept fixed. This configuration also allows future measurements to be taken at different heights and, consequently, at different levels of irradiance incident on the platform.

To study the I-V curve, a variable-load measurement system was adopted, obtained with an adjustable diverter connected to the device's terminals. By varying the resistive load, it is possible to modify the matrix's operating point along the I-V characteristic, as occurs in the experimental measurement of a real photovoltaic module [76]. Furthermore, it allows for the identification of the open-circuit voltage, short-circuit current, and MPP, evaluation of the effect of the bypass diodes, and the variation in performance in the presence of shading. Table 1 shows the values of the resistors used as the load.

Table 1. Load resistance values used for I-V and P-V characterization.

R_{var}	9.8 k Ω
	49.8 k Ω
	100.3 k Ω
	199.6 k Ω
	562.1 k Ω
	0.8 M Ω
	1.7 M Ω
	3.3 M Ω
	5.0 M Ω
	9.9 M Ω

Furthermore, the matrix was designed to allow the operation of a small portion of the system: by leaving one branch of the circuit open, it is possible to electrically isolate two central strings of the matrix, confining the current path exclusively to the central portion. This allows the effect of the blocking diodes to be neglected, since operation involves only a limited number of strings connected to the load.

This operating mode allows us to compare two different experimental conditions. The first, operation of the entire matrix, highlights the effects of the blocking diodes and the interaction between strings, while the second, operation of only the central strings, allows us to study the system response in the absence of the contribution of the blocking diodes.

This possibility is essential for distinguishing the effects introduced by the diodes from the fundamental behavior of the system.

To simulate solar radiation in a controlled environment, a high-intensity white LED source was employed, capable of illuminating the entire LED array and biasing the LEDs operating in receive mode. The light source is shown in Figure 10a.

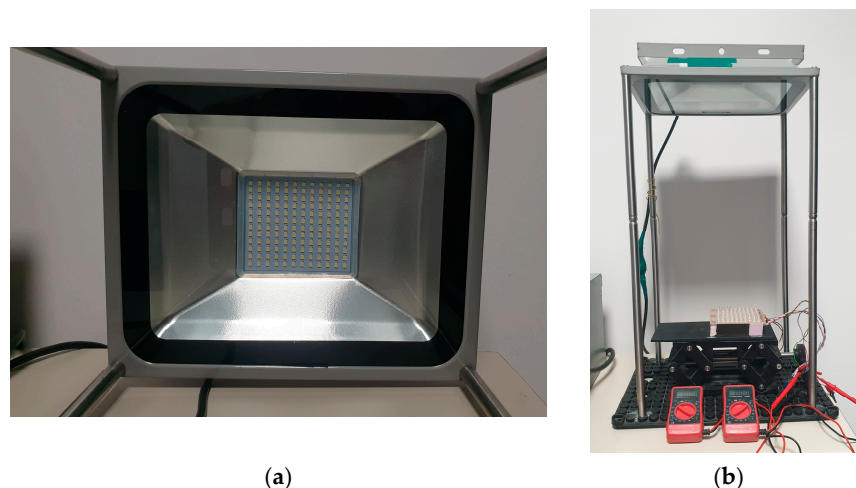


Figure 10. (a) High-intensity white LED light source; (b) experimental setup used for the characterization of the LED matrix.

The entire experimental system is illustrated in Figure 10b. The high-intensity white LED source was fixed to the top of the support structure, while the LED matrix was placed at a fixed distance from the light source (36 cm).

The electrical quantities were acquired using two digital multimeters: one configured as a voltmeter, connected in parallel to the matrix terminals to measure the voltage, and the other configured as an ammeter, connected in series to the circuit to measure the current supplied by the LED matrix operating in receive mode.

4. Analysis of I-V and P Characteristics

The electrical characterization of the device was performed by progressively varying the resistive load applied to the LED matrix. For each load value, the voltage across the device and the current delivered were measured, allowing the reconstruction of the I-V curve.

The variable load allows the circuit's operating point to be varied from short circuit ($R = 0$), where the current increases and the voltage decreases, to open-circuit ($R \rightarrow \infty$), where the current delivered is reduced and the voltage approaches the open circuit voltage.

The data were collected under three operating conditions:

1. Absence of shading;
2. Shading with active bypass diodes;
3. Finally, shading without bypass diodes.

4.1. Matrix Data Analysis

Figure 11 shows the LED matrix under absence of shading (a) and under shading with active bypass diodes (b).

Figure 12 shows the comparison between the I-V characteristics obtained under three operating conditions.

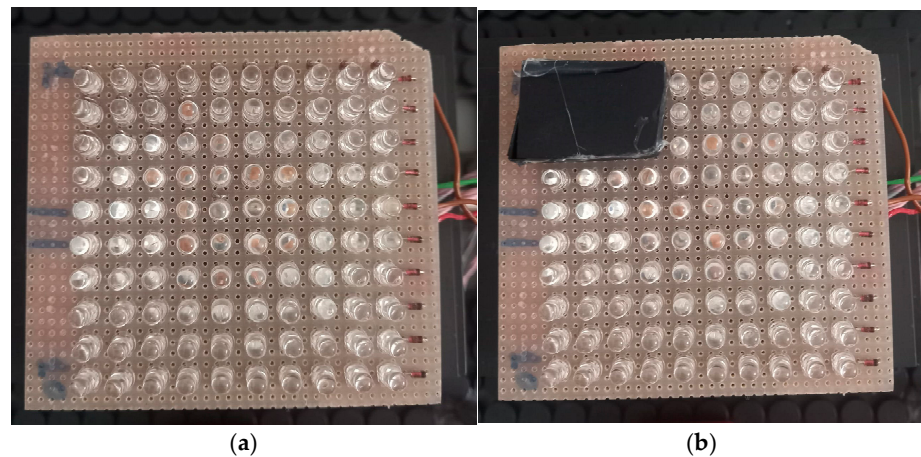


Figure 11. Experimental apparatus of the matrix under conditions: (a) without shade and (b) shaded with bypass diodes.

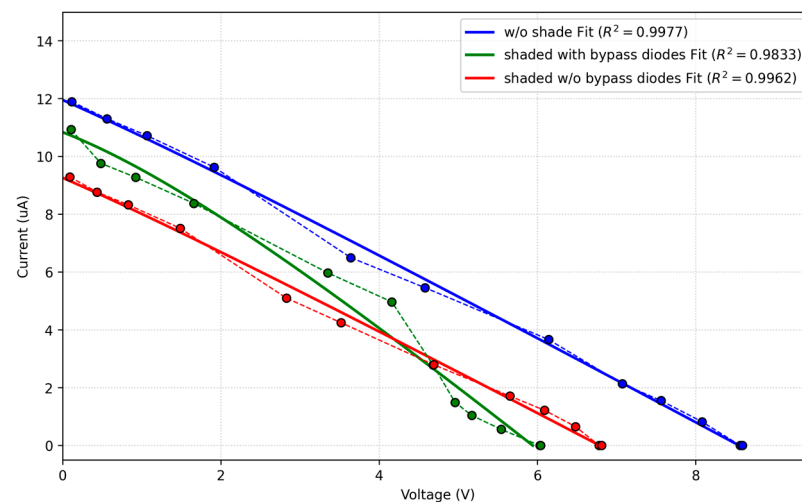


Figure 12. Experimental I–V curves of the LED matrix in the three irradiation conditions considered, compared with the fitting. Dashed lines have been obtained from experimental measurements while the continuous line are the fit ones.

Under uniform illumination, the I–V curve exhibits a similar behavior to that of photovoltaic devices: the current remains approximately constant for low voltage values and decreases near the open-circuit voltage.

To mathematically validate the proposed platform, a nonlinear regression was performed by comparing the I–V curves experimentally obtained from the LED array with the theoretical equation of the single-diode model (Equation (1)). The parameters estimated through the fitting process are reported in Table 2.

Table 2. Single-diode model parameters estimated by the fitting process for LED matrix.

Condition	R^2	I_{ph} (μA)	n	R_s (Ω)
Not shaded	0.9977	14.273	15.42	0.65
Shaded with bypass diodes	0.9833	12.051	24.61	0.41
Shaded w/o bypass diodes	0.9962	12.051	12.27	0.67

The quality of the fit was assessed using the coefficient of determination (R^2), which showed a high agreement between the experimental data and the theoretical model.

The device's power was calculated for each point and shows a well-defined maximum, i.e., MPP (Figure 13).

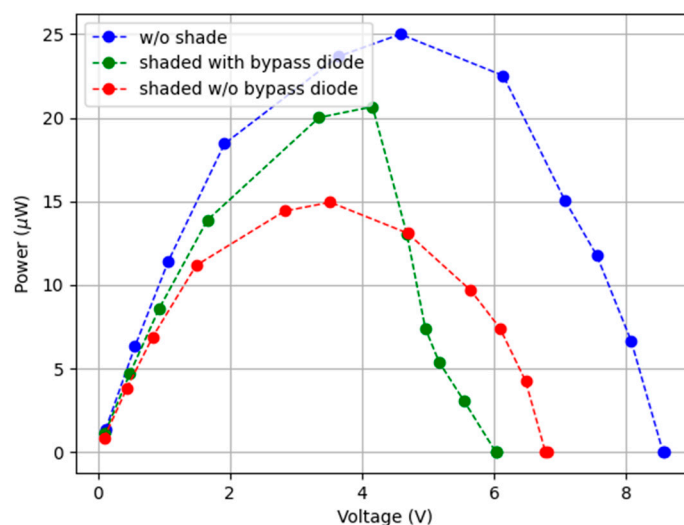


Figure 13. P-V curves of the LED matrix in the three experimental conditions considered.

Introducing shading shows a reduction in the generated current and a deformation of the characteristic curve.

Without bypass diodes, the current is limited to the less illuminated portion of the system, showing a decrease in current with a reduction in the maximum available voltage. Under this condition, the shaded string acts as a limiting element of the entire structure, significantly reducing the extractable power.

Introducing bypass diodes changes the system's behavior significantly: in the initial region, the current remains higher than without the bypass, followed by a drop near the diode activation voltage. This is attributable to the conduction of the bypass diodes, which electrically exclude the less illuminated sections and allow the current to flow through alternative paths. The presence of the discontinuity point in the bypass diode curve provides experimental evidence of the activation of the alternative current path, similar to what occurs in commercial photovoltaic modules subjected to partial shading.

The maximum power is higher than the non-bypass configuration. However, a drop in power is observed due to the activation of the diodes, which modify the device's operating point.

4.2. String Data Analysis

Figure 14 shows the configuration of the LED matrix in which only the central string is active, while the LED associated with the bypass diode is intentionally shaded.

Similarly to what was observed for the entire matrix, Figure 15 reports the corresponding I-V curves obtained for the central strings.

In this case, the fitting was also performed using the single-diode model (Equation (1)), and the values of the coefficient of determination R^2 confirm the high quality of the fit between the theoretical model and the experimental data, further validating the proposed method. The parameters estimated through the fit are reported in Table 3.

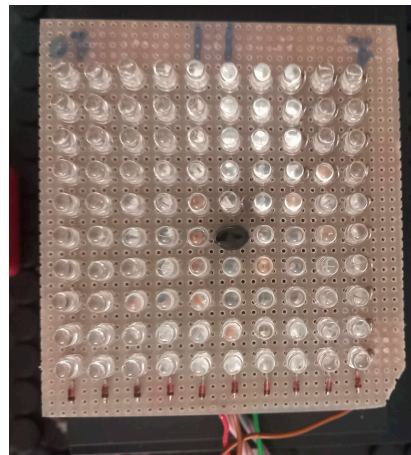


Figure 14. Experimental apparatus of the shaded string with bypass diode.

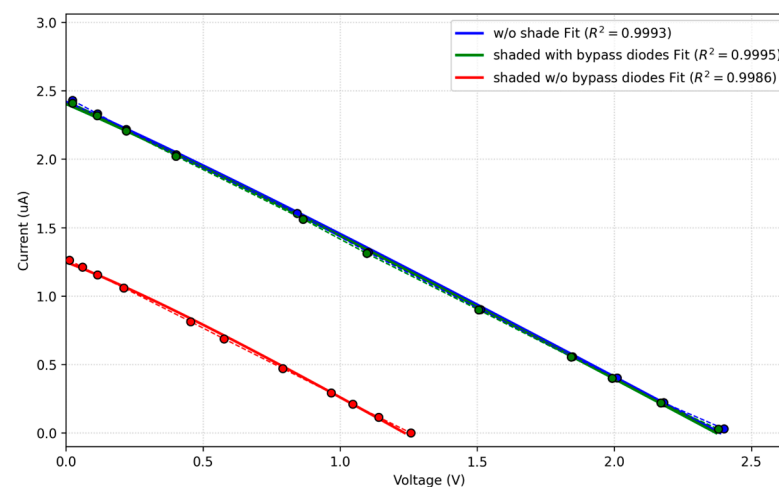


Figure 15. Experimental I–V curves of the central strings of the LED matrix in the three irradiation conditions considered, compared with the fitting. Dashed lines have been obtained from experimental measurements while the continuous line are the fit ones.

Table 3. Single-diode model parameters estimated by the fitting process for the central strings of the array.

Condition	R^2	I_{ph} (μA)	n	R_s (Ω)
Not shaded	0.9993	2.916	5	0.89
Shaded with bypass diodes	0.9995	2.890	5	0.89
Shaded w/o bypass diodes	0.9986	1.514	5	0.81

Figure 16 instead shows the corresponding P–V curves obtained for the central strings in the three experimental conditions considered.

An analysis of the I–V curve shows that in the case of uniform illumination and in the presence of shading with bypass diodes, the curve coincides, and the corresponding P–V curve shows a single peak for each configuration.

Conversely, in the case of shading without bypass diodes, a significant reduction in the current output is observed, with a consequent decrease in voltage and power. Indeed, in this configuration, the shaded portion limits the entire string. Power is also significantly reduced, and the MPP shifts toward lower voltage values.

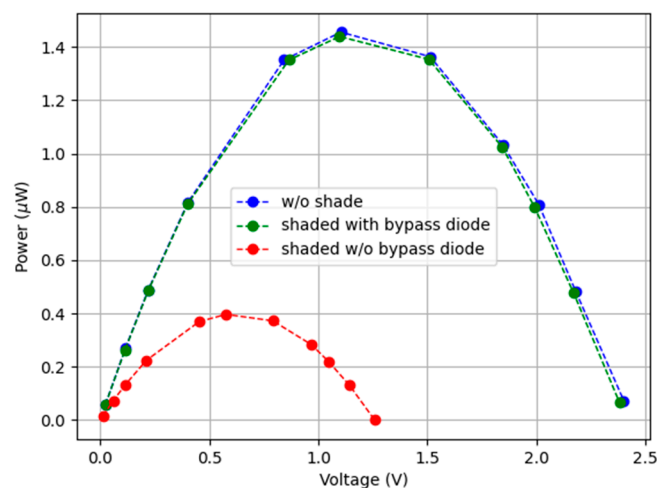


Figure 16. P-V curves of the central strings of the LED matrix in the three experimental conditions considered.

5. Discussions

The main electrical parameters obtained from the experimental curves are reported in Table 4.

Table 4. Main electrical parameters extracted from the experimental I-V and P-V curves.

Configuration	Condition	I_{sc} (μA)	V_{oc} (V)	P_{max} (μW)
Matrix electrical parameters	Not shaded	11.9	8.6	25.0
	Shaded with bypass diodes	10.9	6.0	20.5
	Shaded w/o bypass diodes	9.3	6.8	15.0
String electrical parameters	Not shaded	2.4	2.4	1.5
	Shaded with bypass diodes	2.4	2.4	1.4
	Shaded w/o bypass diodes	1.3	1.3	0.4

The results show how shading the array reduces the short-circuit current and maximum deliverable power. Without bypass diodes, the short-circuit current decreased from 11 μA to 9.3 μA , while the maximum power decreased from 25.0 μW to 15.0 μW , corresponding to a loss of approximately 40%.

Inserting bypass diodes allows for partial energy recovery, limiting the effects of mismatch between strings. The data show an increase in power from 15.0 μW to 20.5 μW , with a recovery of 36.7%. This improvement is due to the ability of the bypass diodes to electrically exclude the less illuminated areas, preventing them from acting as passive loads for the rest of the array. However, the open-circuit voltage is reduced compared to the nominal case, since excluding the shaded sections results in an overall decrease in the available voltage at the device terminals.

In contrast, in the configuration of only the central strings, the values of I_{sc} , V_{oc} and P_{max} are unchanged in the presence of bypass diodes. This confirms that the influence of the blocking diodes becomes negligible and the electrical behavior is dominated by the intrinsic response of the LEDs.

From a physical standpoint, the device is able to correctly reproduce the main phenomena observed in photovoltaic systems, such as current reduction due to shading, power loss due to mismatch, partial recovery via bypass, modification of the maximum power point, and dependence on the number of active strings.

The quality of the adaptation was assessed through the fit and determination of the coefficient of determination R^2 , which showed a high agreement between the experimental data and the theoretical model. The values obtained confirm that, despite the low cost of the components used, the platform is capable of providing accurate, reproducible measurements that are consistent with the reference mathematical model. These results demonstrate the reliability of the platform as an efficient, simplified emulator of a photovoltaic field and confirm its suitability for laboratory use.

However, the system has some limitations compared to a standard photovoltaic generator:

- Reduced sensitivity of the LEDs in reception mode;
- Spectral response not equivalent to photovoltaic cells;
- Greater dispersion of characteristic parameters between individual components;
- Significantly lower current values.

In conclusion, the system developed should not be considered a substitute for a real panel for energy analysis. However, it represents a compact, economical, and reliable experimental tool for studying the fundamental electrical phenomena that govern photovoltaic fields.

6. Conclusions

In this work, an experimental device based on an LED array in reception mode was developed as an educational emulator of a photovoltaic field. The results show that the system can faithfully reproduce the main phenomena of photovoltaic fields, including the I-V and P-V characteristic curves, the power curve, the effects of partial shading, and the role of bypass and blocking diodes. Analysis of the experimental curves highlighted how the proposed configuration allows for the observation of the influence of different system operating conditions. In particular, the comparison between the full array and the configuration limited to strings alone allowed for the contribution of the protection devices to be distinguished. When fully operational, the LED matrix produces 25.0 μW of power, which is the reference for any subsequent analysis performed after modifying the work operative conditions. For example, if shading occurs by covering 12% of the LEDs, the bypass diodes activate, resulting in a decrease in power output of approximately 20%; without them, the output decreases by 40%.

Despite its limitations, the device has proven to be an effective, low-cost tool for educational applications. Its simplicity, the flexibility of its different configurations, and the ability to control shading conditions make the device an excellent solution for the experimental study of photovoltaic phenomena in a controlled environment.

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