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Theme

**Design and implementation of a photovoltaic (PV)
analyser based on an Arduino microcontroller**

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Dedication

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List of Abbreviations:

ADC: Analog-to-Digital Converter

CSV: Comma-Separated Values

DAC: Digital-to-Analog Converter

DAQ: Data Acquisition System

DC: Direct Current

AC: Alternating Current

FF: Fill Factor

I²C: Inter-Integrated Circuit Protocol

I-V: Current-Voltage

MOSFET: Metal-Oxide-Semiconductor Field-Effect Transistor

MPP: Maximum Power Point

MPPT: Maximum Power Point Tracking

OLED: Organic Light-Emitting Diode

PC: Personal Computer

P-N: Positive-Negative (Junction)

P-V: Power-Voltage

PWM: Pulse Width Modulation

RC: Resistor-Capacitor

STC: Standard Test Conditions

V_{oc}: Open-Circuit Voltage

I_{sc}: Short-Circuit Current

V_{mpp}: Voltage at Maximum Power Point

I_{mpp}: Current at Maximum Power Point

P_{max}: Maximum Output Power

Wi-Fi: Wireless Fidelity

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Table of symbols:

Symbol	Description	Unit	Symbol	Description	Unit
D-n	12-bit digital input code (0 to 4095)	-	Q	Electron charge ($1,602 \times 10^{-19}$)	C
FF	Fill factor	-	RDS_(on)	Drain-source on-resistance	Ω
G	Solar irradiance	W/m ²	Rs	Series resistance	Ω
I	Output current of pv cell	A	Rsh	Shunt resistance	Ω
I₀	Reverse saturation current of diode	A	Rth	Thermal resistance	°C/W
I_D	Drain current	A	Rth(h-a)	Heatsink to ambient thermal resistance	°C/W
I_d	Diode current	A	Rth(j-c)	Junction to case thermal resistance	°C/W
I_{MP}	Current at maximum power point	A	V_t	Thermal voltage (KT/q)	V
I_{ph}	Photocurrent (light-generated current)	A	T	Temperature	°C/K
I_{SC}	Short-circuit current	A	T_A	Ambient Temperature	°C/K
I_{sh}	Shunt current	A	T_J	Junction temperature	°C/K
L	inductor	H	V	PVoutput voltage	V
N	Diode ideality factor	-	V_{DS}	Drain-to source voltage	V
n_s	Number of series-connected cells	-	V_{GS}	Gate to source voltage	V
P	power	W	V_{GS(th)}	Gate-to threshold voltage	V
P_D	Power dissipation	W	τ	Time constant	s
p_{max}	Maximum power	W	η	efficiency	%

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Abstract:

This thesis presents the design and implementation of a low-cost photovoltaic analyser based on the Arduino Mega 2560 microcontroller. The developed system is capable of automatically generating current-voltage (I-V) and power-voltage (P-V) characteristic curves for various solar modules, using an INA219 current and voltage sensor, an MCP4725 12-bit I²C DAC for precise gate voltage control, and an IRLZ44N MOSFET as a controllable electronic load. The system acquires more than 2000 data points per sweep in less one minute, and transmits the data in real time to a PC via serial communication for visualization in Microsoft Excel. Experimental validation was conducted on three photovoltaic sources of increasing power levels under real outdoor conditions. A comparative evaluation against the conventional manual method using a rheostat and digital multimeters confirmed the reliability of the proposed system, demonstrating clear advantages in measurement speed, data resolution, and curve quality. The results prove that frugal engineering principles can deliver scientifically meaningful PV characterization at a fraction of the cost of commercial solutions.

Keywords: Photovoltaic analyser, Arduino, I-V curve, P-V, INA219, MCP4725, MOSFET, low cost.

Résumé :

Ce mémoire présente la conception et la réalisation d'un analyseur photovoltaïque à faible coût basé sur le microcontrôleur Arduino Méga 2560. Le système développé est capable de générer automatiquement les courbes caractéristiques courant-tension (I-V) et puissance-tension (P-V) pour différents modules solaires, en utilisant un capteur de courant et de tension INA219, un convertisseur numérique-analogique MCP4725 12 bits I²C pour le contrôle précis de la tension de grille, et un transistor MOSFET IRLZ44N comme charge électronique contrôlable. Le système acquiert plus de 2000 points de mesure par balayage en moins d'une minute, et transmet les données en temps réel vers un PC via communication série pour visualisation dans Microsoft Excel. La validation expérimentale a été effectuée sur trois sources photovoltaïques de puissances croissantes dans des conditions extérieures réelles. Une évaluation comparative avec la méthode manuelle conventionnelle utilisant un rhéostat et un multimètre numérique a confirmé la fiabilité du système proposé, démontrant des avantages clairs en termes de vitesse de mesure, de résolution des données et de qualité des courbes. Les résultats prouvent que les principes de l'ingénierie frugale peuvent fournir une caractérisation photovoltaïque scientifiquement significative à une fraction du coût des solutions commerciales.

Mots-clés : Analyseur photovoltaïque, Arduino, courbe I-V, INA219, MCP4725, MOSFET, instrumentation à faible coût.

ملخص :

تقدّم هذه المذكرة تصميم وتحقيق جهاز تحليل كهروضوئي منخفض التكلفة مبني على متحكم Arduino Mega 2560. يتميز النظام المطور بقدرته على توليد منحنيات الخصائص الكهربائية للتيار والجهد (I-V) والقدرة والجهد (P-V) بشكل تلقائي لمختلف الوحدات الشمسية، وذلك باستخدام مستشعر INA219 لقياس التيار والجهد، ومحول رقمي-تمائلي MCP4725 ذي 12 بت يعمل عبر بروتوكول I²C للتحكم الدقيق في جهد البوابة، وترانزستور MOSFET من نوع IRLZ44N كحمل إلكتروني قابل للتحكم. يسجل النظام أكثر من 2000 نقطة قياس لكل عملية مسح في أقل من دقيقة واحدة، وينقل البيانات في الوقت الحقيقي إلى الحاسوب عبر الاتصال التسلسلي للتصوير في Microsoft Excel. أُجري التحقق التجريبي على ثلاثة مصادر كهروضوئية ذات قدرات متصاعدة في ظروف خارجية حقيقية. وقد أكدت المقارنة مع الطريقة التقليدية باستخدام المقاومات المتغيرة والمولتي متر الرقمي موثوقية النظام المقترح، مُظهرةً مزايا واضحة من حيث سرعة القياس ودقة البيانات وجودة المنحنيات. تُثبت النتائج أن مبادئ الهندسة الاقتصادية قادرة على تقديم توصيف كهروضوئي ذي قيمة علمية حقيقية بتكلفة تُعدّ جزءاً بسيطاً من تكلفة الحلول التجارية المتاحة.

الكلمات المفتاحية: محلل كهروضوئي، Arduino، منحني I- V، مستشعر INA219، محول MCP4725، ترانزستور MOSFET، أجهزة قياس منخفضة التكلفة.

GENERAL INTRODUCTION

I . General Introduction:

1. Background and Problem Statement:

The global demand for energy continues to rise dramatically due to population growth, industrialization, and the increasing reliance on electronic devices. According to the International Energy Agency, total primary energy consumption reached approximately 650 EJ in 2024, with fossil fuels still accounting for nearly 80% of the global energy mix (IEA, 2025). Under the Current Policies Scenario (CPS) outlined in the IEA's World Energy Outlook 2025, primary energy consumption could increase by around 15% by 2035, driven primarily by emerging economies (IEA, 2025). This persistence of fossil fuels contributes significantly to global CO₂ emissions, which are projected to remain close to 40 gigatonnes per year well into the 2030s (IEA, 2025).

While fossil fuels remain dominant, the environmental consequences have accelerated the global shift toward sustainable energy sources. According to the International Renewable Energy Agency, renewable energy capacity additions reached a record 692 GW in 2025, accounting for 85.6% of global electricity expansion (IRENA, 2026). Solar energy alone grew by 511 GW, representing nearly 75% of all renewable capacity additions. Cumulative installed solar PV capacity reached approximately 2.4 TW by the end of 2025, making solar the fastest-growing source of renewable energy worldwide (IRENA, 2026).

2. Importance of Photovoltaic Characterization:

Solar PV energy is abundant and can be converted directly into electricity without moving parts or harmful emissions. However, PV module performance is highly dependent on environmental conditions, such as solar irradiance and cell temperature, as well as the intrinsic characteristics of the modules. Standard Test Conditions (STC) provide a reference performance, but real-world operating conditions vary significantly (IEC, 2007). To design, install, and maintain efficient PV systems, engineers need accurate and reliable tools to characterize the current–voltage (I–V) and power–voltage (P–V) curves of PV modules under realistic scenarios (IEC, 2011).

3. Economic Cost as a Barrier to Commercial Characterization:

Educational institutions and small-scale laboratories in developing regions face severe difficulties in acquiring commercial I–V curve tracers and Data Acquisition (DAQ) systems due to their high cost, which ranges between \$2,000 and \$10,000. This financial challenge

creates a pressing need to develop and construct alternative, low-cost, and open-source measurement and characterization tools to ensure the continuity of scientific research.

4. Frugal Innovation and Open-Source Solutions:

The concept of "frugal engineering" achieving essential functionality with minimal resources has gained attention. The Arduino platform, combined with affordable sensors, represents a quintessential frugal innovation. By using an Arduino Mega 2560 and carefully selected components, it is possible to build a PV characterization system that achieves sufficient accuracy for educational and research applications at a fraction of the cost of commercial alternatives. Previous studies have demonstrated that open-source hardware can provide reliable PV analyzer (Motahhir et al., 2018), promoting hands-on learning in renewable energy engineering.

5. Objectives of the Thesis:

The main objective of this thesis is to design, implement, and validate a low-cost, Arduino-based PV analyzer capable of automatically tracing the I–V and P–V characteristics of PV modules. Specifically, the work aims to:

- Establish a theoretical foundation covering PV cell physics, the single-diode equivalent circuit model, and key performance parameters.
- Evaluate conventional manual characterization methods and demonstrate the efficiency and superiority of the proposed automated technique.
- Propose a frugal engineering solution using an Arduino Mega 2560, an IRLZ44N MOSFET as an electronic load, and an INA219 digital sensor.
- Design the necessary control circuitry, including an RC low-pass filter to manage MOSFET gate control.
- Develop embedded software to implement an automated sweep algorithm, format data as CSV, and stream it in real time via USB.
- Integrate robust safety protocols, including overcurrent and overtemperature protection.
- Validate the system through experimental measurements and compare results with theoretical models.

6. Thesis Outline:

This thesis is organized into four main chapters:

- **Chapter 1:** establishes the scientific background, covering the physics of the p-n junction, the single-diode equivalent circuit model, and critical parameters (V_{OC} , I_{SC} , FF, MPP).

- **Chapter 2:** compares traditional manual measurement techniques with modern automated approaches, introduces the Arduino platform as a frugal innovation, and covers the principles of MOSFET-based electronic loads and data communication protocols.

- **Chapter 3:** presents the core engineering contribution. It details the system architecture, hardware selection, thermal management design, control circuitry, software sweep logic, and safety protocols implemented to ensure reliable operation.

- **Chapter 4:** presents experimental results, evaluating the accuracy and repeatability of the prototype and providing a comparative analysis between experimental data and theoretical models

Chapter 1: Fundamentals of Photovoltaic Energy

I - Introduction:

Driven by the global climate crisis, photovoltaic (PV) technology has emerged as a premier emission-free energy solution capable of converting sunlight directly into electricity (“Climate Change 2022 - Mitigation of Climate Change,” 2023; Net Zero by 2050, n.d.). Theoretically rooted in the photoelectric effect advanced by Einstein (THE PARIS AGREEMENT, 2016), modern PV engineering began with Bell Laboratories' first 6% efficient silicon p-n junction in 1954 (Masters, 2013). Today, continuous innovation has scaled these devices into global, gigawatt-capacity commercial power systems (World Energy Outlook 2023, n.d.).

Comprehensive PV system analysis demands a multidisciplinary foundation spanning semiconductor physics, quantum mechanics, and electrical engineering. The solar cell's operation governed by photon-semiconductor interactions and carrier separation across the p-n junction imposes fundamental limits on conversion efficiency (Renewable Energy Agency, 2023).

Accordingly, this chapter establishes the critical theoretical framework for this study. It addresses solar radiation, semiconductor physics, and p-n junction mechanics, followed by operational models and key cell parameters. Lastly, it reviews current commercial PV technologies, environmental factors inducing degradation, and performance evaluation under both standard and real-world operating conditions (Global Solar Atlas 2.0, n.d.; Renewable Energy and Jobs, n.d.). Ultimately, this groundwork provides the analytical tools required to interpret and evaluate PV behavior in the subsequent sections of this work.

1.1. Introduction to solar energy:

The significant increase in global energy demands, coupled with the escalating rate of climate change, has put renewable energy and, in particular, solar photovoltaic technology in the midst of global energy transition strategies. Global primary energy consumption in 2022 was around 604 EJ, with fossil fuels still dominating 80% of the global supply, resulting in a record level of CO₂ emissions of 36.8 Gt in 2022 (Luque & Hegedus, 2011; RENEWABLES 2023 GLOBAL STATUS REPORT, n.d.). As a result, a binding international agreement was signed in 2015 in Paris, committing to a global warming level of "well below 2 °C above pre-industrial levels," thereby making clean energy a necessity rather than a want (Einstein, 1905). Of all the renewable energy sources, solar PV has proven to be one of the most promising. In fact, the Sun provides the Earth's surface with approximately 885,000 PWh of energy annually,

Chapter 01: Fundamentals of Photovoltaic Energy

which is over 5,000 times the total human energy demand. This has made solar energy virtually inexhaustible (Chapin et al., 1954). With a decline in the levelized cost of electricity (LCOE) by a staggering 89% between 2010 and 2022, global solar PV capacity has crossed the milestone of 1.2 TW by the end of 2022. Moreover, annual installations have surpassed the milestone of 200 GW. According to the International Energy Agency (IEA), solar PV has to contribute almost 33% of global electricity demand by the year 2050 to meet the Net Zero Emissions scenario. In fact, solar PV would be the largest source of electricity in the world by then. The importance of PV energy does not end here. As the world is still struggling to provide access to electric power for the remaining 775 million people in the world by the end of 2022 (Green, 1982) PV systems can provide a viable solution for the electrification of the rural population in developing countries (Nelson, 2003). From an economic perspective, the solar industry has already provided employment for around 4.3 million people worldwide by the end of 2022 (Markvart & Castaner, 2003) besides lowering the energy bills for consumers around the globe. Moreover, the regions that enjoy high solar irradiance levels, such as North Africa with annual GHI exceeding 2500 kWh/m²/year (Masters, 2005), can take advantage of this resource not only for meeting local energy needs but also for the export of energy.

1.2 Physics of the Solar Cell: The P-N junction and the photovoltaic effect:

1.2.1 The P-N junction:

A solar cell is mainly built from silicon (Si), which is used in almost all types of solar cells. Silicon is a semiconductor, meaning it can conduct electricity, but not very well in its pure form. To improve its electrical behavior, tiny amounts of other elements are added in a process called doping. This process allows the creation of two types of layers inside the silicon crystal:

▪N-type layers:

These layers are made by adding elements like arsenic or antimony. These elements bring extra electrons into the silicon, which are free to move around. These electrons act as negative charge carriers and help the material conduct electricity more easily.

▪P-type layers:

These layers are created by adding elements like gallium or indium. This introduces holes, which are places where electrons are missing. These holes behave as positive charge

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carriers and allow electric current to flow through the material. (PV Education & Kalogirou2013).

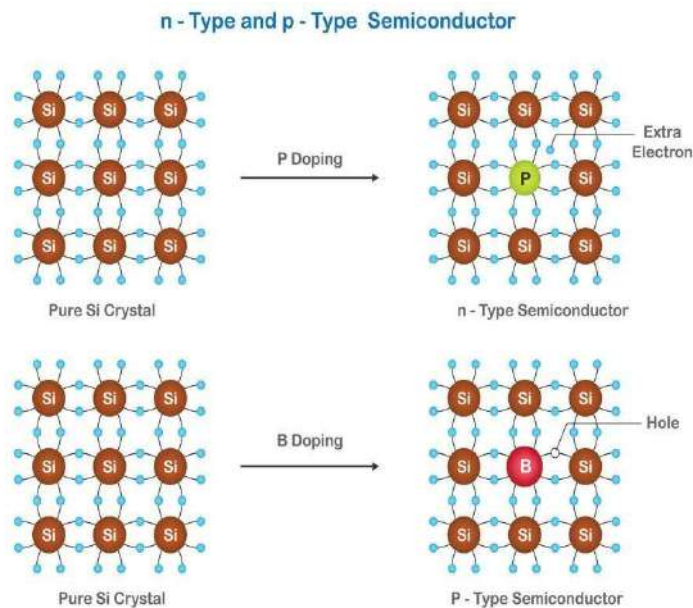


Figure 1-1: Formation of N-type and P-type semiconductors through doping in silicon.

▪The P–N Junction:

The most important feature of a solar cell is when the N-type and P-type layers are joined together to form a P–N junction. At this junction, electrons from the N-type layer move to fill holes in the P-type layer, and holes from the P-type layer move toward the N-type layer. This exchange creates a small area called the depletion region, where very few free charges are left.

This movement of charges generates an internal electric field, which works like a one-way gate, guiding electrons and holes to move in a specific direction. This gives the junction a diode-like behavior, allowing current to flow more easily in one direction than the other. From an energy perspective, the silicon needs about 1.11 eV to free electrons and generate current when light shines on the cell. [Kalogirou,2013], (PV Education).

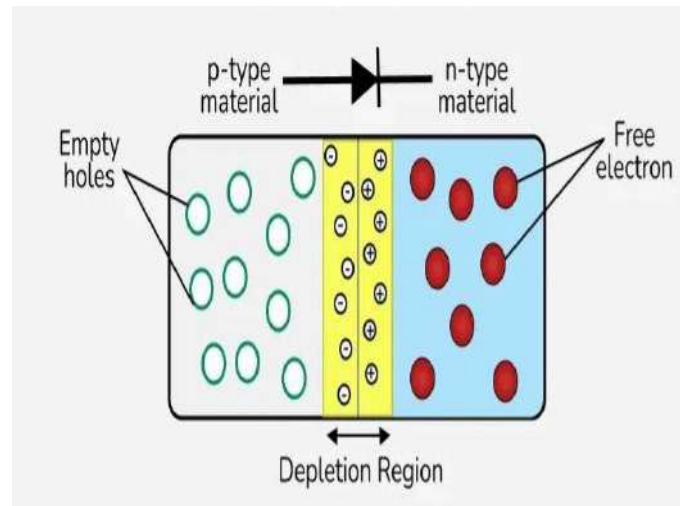


Figure 1-2: Structure of a P-N junction showing the depletion region and charge distribution between P-type and N-type materials.

1.2.2 The Photoelectric Effect:

If we want to understand how a solar cell turns sunlight into electricity, we need to start with a simple but powerful idea: light can behave like a stream of tiny particles. This idea, first proposed by Albert Einstein in 1905, is known as the photoelectric effect. Einstein suggested that light is made up of small packets of energy called photons, and this discovery later earned him the Nobel Prize in Physics in 1921 (Halliday, Resnick, & Walker, 2014, chapter 38, p. 1154-1156).

The energy carried by each photon is not random. It depends on the light's frequency. The higher the frequency, the more energy the photon carries. This relationship is described by the equation:

$$E = hf \quad (1-1)$$

where E is the photon energy, h is Planck's constant, and f is the frequency of light. This equation tells us, for example, that blue light (with higher frequency) carries more energy per photon than red light (with lower frequency) (Halliday, Resnick, & Walker, 2014, Chapter 38, p. 1154-1156).

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When a photon strikes a metal surface, it can knock an electron out of the metal. This is called the external photoelectric effect, and it can be observed in laboratory experiments using a setup like the one shown in Figure 3 (Halliday, Resnick, & Walker, 2014, p. 1156).

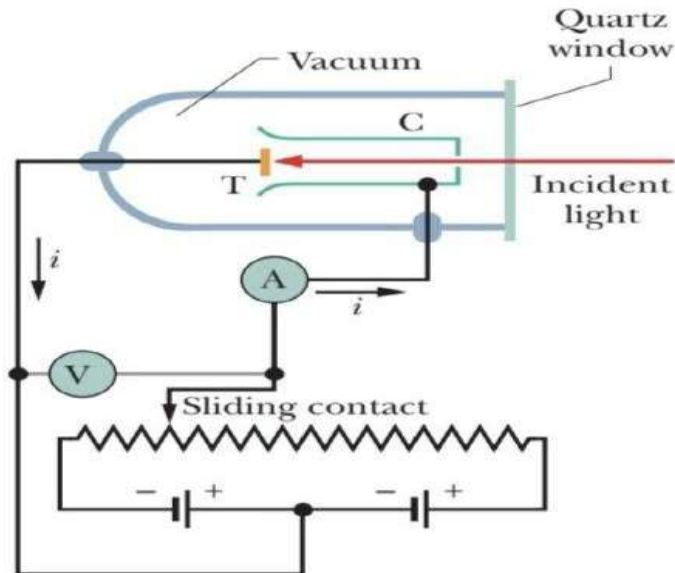


Figure 1-3: Schematic diagram of an apparatus used to study the external photoelectric effect. Incident light ejects electrons from the target, which are collected to produce a current (Halliday, Resnick, & Walker, 2014, p. 1156)

However, in a solar cell, something slightly different happens. The material used is not a metal but a semiconductor, and the photon is absorbed inside the material. If the photon's energy is high enough at least equal to the semiconductor's bandgap energy it can transfer its energy to an electron. That electron then jumps from the valence band (VB) to the conduction band (CB), where it can move freely. The empty space it leaves behind is called a hole, and together they form what is known as an electron-hole pair. As illustrated in Figure 4, this process is called the internal photoelectric effect, and it is the key mechanism behind solar cell operation (Marque Lameirinhas et al., 2022)

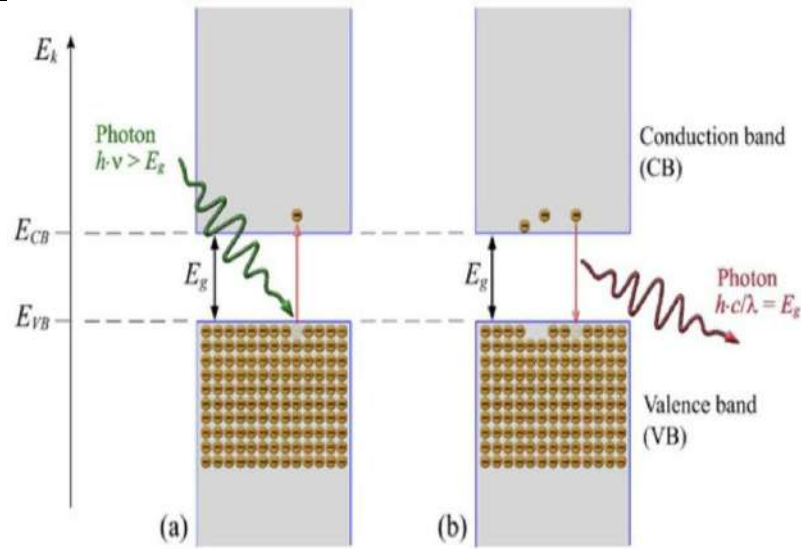


Figure 1-4: Schematic diagram of the internal photoelectric effect in a semiconductor. (a) A photon with energy greater than the bandgap excites an electron from the valence band (VB) to the conduction band (CB), creating an electron-hole pair. (b) The relationship between photon wavelength and bandgap energy.

Once the electron-hole pair is created, the electron and hole need to be separated to generate a current. This separation happens because of the built-in electric field inside the p-n junction. The electric field pushes the electron toward the n-type side and the hole toward the p-type side, as illustrated in Figure 4.

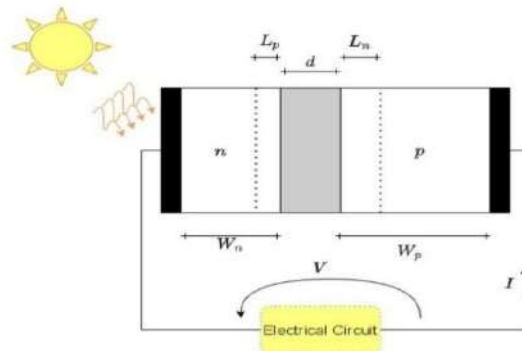


Figure1- 5: Diagram of a p-n junction solar cell. (Marques Lameirinhas et al.,2022, p.13)

If we connect an external circuit, these charges will flow, producing an electric current that we can use (Marques Lameirinhas et al., 2022).

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It is worth mentioning that not every photon that hits the solar cell will be useful. Photons with energy lower than the bandgap simply pass through the material without being absorbed. Photons with energy higher than the bandgap are absorbed, but the extra energy is wasted as heat a loss known as thermalization. These limitations explain why solar cells cannot convert all the sunlight they receive into electricity (Marques Lameirinhas et al., 2022).

In summary, the photoelectric effect is the foundation of how solar cells work. It describes how light, made of photons, can create moving charges inside a semiconductor. The p-n junction then takes those charges and turns them into a steady flow of electricity. Together, these two principles make it possible to harvest energy from the sun.

1.3 Equivalent Circuit Models:

1.3.1 The Single-Diode Model:

To make accurate predictions of the behavior of PV devices under varying conditions, engineers typically use equivalent circuit models to analyze their performance. The most commonly used model is the single-diode model because it combines simplicity with sufficient accuracy for most engineering applications. This model consists of a photocurrent generator, I_{ph} , which produces current proportional to the incident solar irradiance, connected in parallel with a diode that represents the p-n junction of the semiconductor material. The diode governs the non-linear electrical characteristics of the cell. However, real PV cells exhibit internal power losses that are not captured by this simplified version. Therefore, two parasitic resistances are incorporated into the model. A small series resistance R_s , accounts for resistance to current flow through the semiconductor bulk and metallic contacts. A large parallel (shunt) resistance R_{sh} , models leakage currents across the p-n junction. While an ideal PV cell would have $R_s = 0$ and $R_{sh} = \infty$, accurately determining the actual values of these resistances is essential for developing a realistic current-voltage (I-V) curve, particularly near the maximum power point. For a PV module or array, this single-diode circuit can be scaled by connecting multiple cells in series and/or parallel configurations. Figure 6 illustrates this evolution, showing the ideal cell model without resistances on the left and the complete practical model on the right." (Villalva, Gazoli, & Ruppert, 2009).

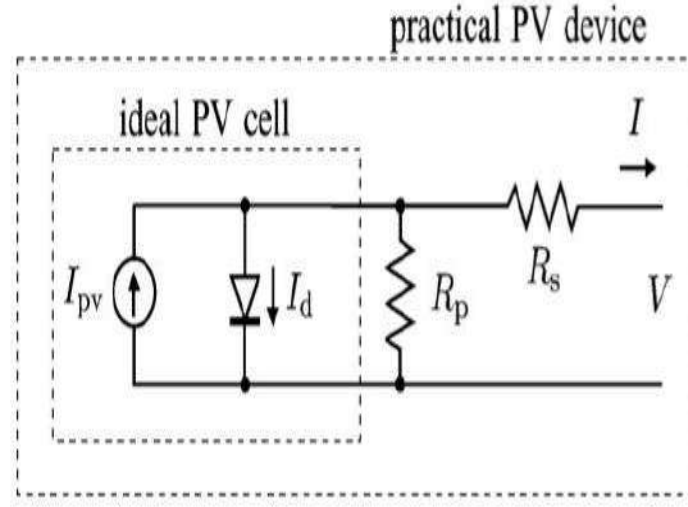


Figure1- 6: Single-diode equivalent circuit of a photovoltaic cell: (left) ideal cell model consisting of a photocurrent source and a diode; (right) practical PV device model including series resistance R_s and parallel (shunt) resistance R_p . (Villalva, Gazoli, & Ruppert,2009)

1.3.2 Mathematical Model of the PV Cell:

The mathematical representation of a photovoltaic cell is derived by applying Kirchhoff's current law to its single-diode equivalent circuit. As illustrated in Figure 6, this circuit comprises a current source representing the photogenerated current I_{ph} , a diode that models the p-n junction behavior, a series resistance R_s , and a shunt resistance R_{sh} . The output current I is obtained by subtracting both the diode current I_d and the shunt branch current I_{sh} from the photocurrent I_{ph} . The diode current follows the Shockley equation, which captures the exponential relationship between current and voltage across the junction. While the shunt current is given by $I_{sh} = (V + IR_s)/R_{sh}$ according to Ohm's law. After incorporating the voltage drop across R_s , the complete implicit current-voltage relationship is given by:

$$I = I_{ph} - I_0 \left[\exp \left(\frac{V + IR_s}{nV_t} \right) - 1 \right] - \frac{V + IR_s}{R_{sh}} \quad (1-2)$$

where I_0 is the reverse saturation current of the diode, n is the ideality factor (typically between 1 and 2), and $V_t = kT/q$ is the thermal voltage, with k being Boltzmann's constant (1.381×10^{-23} J/K), T the absolute temperature in Kelvin, and q the electron charge (1.602×10^{-19} C). For a PV module composed of N_s cells connected in series, the thermal voltage term

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is scaled accordingly, modifying the exponential argument to $V + I R_s$ divided by $n N_s V_t$. Equation (2) is transcendental because the current I appears on both sides, making an explicit analytical solution impossible. Consequently, numerical methods or iterative algorithms must be employed to solve for I at a given voltage. This characteristic is particularly relevant for low-cost embedded systems such as Arduino-based analyzers, which must implement efficient numerical solvers to reconstruct the I-V curve from measured data (Villalva, Gazoli, & Ruppert, 2009; Shongwe & Hanif, 2015).

1.4 Critical Parameters of a Photovoltaic Cell:

The performance of a photovoltaic (PV) cell is evaluated using several electrical parameters derived from the current–voltage (I–V) characteristic curve. These parameters provide important information about the electrical behavior and efficiency of the solar cell under illumination. The most important parameters include the open-circuit voltage (V_{oc}), the short-circuit current (I_{sc}), the fill factor (FF), and the maximum power point (MPP). The following figure illustrates the I–V curve and the location of these critical points.

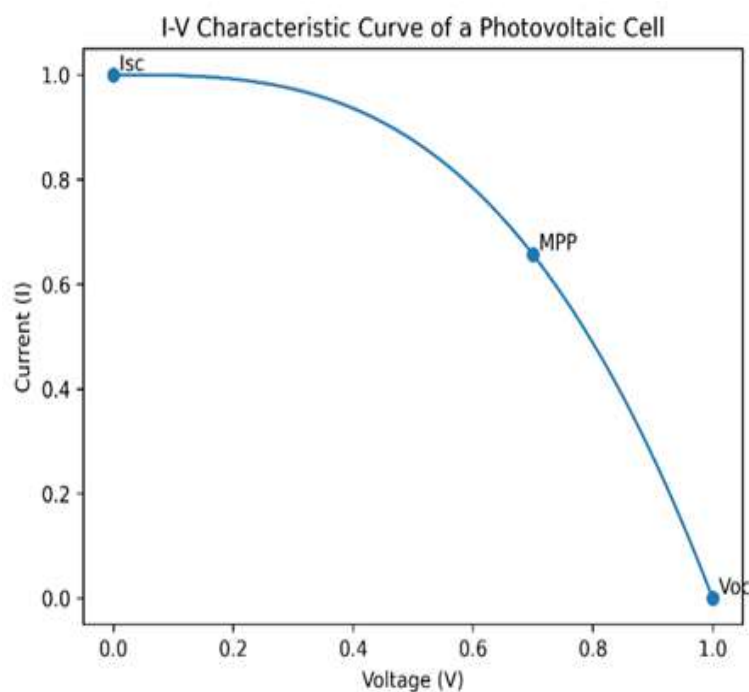


Figure 1-7: I-V Characteristic curve of a Photovoltaic Cell.

1.4.1 Open-Circuit Voltage (Voc):

The open-circuit voltage (Voc) represents the maximum voltage that a photovoltaic cell can produce when no external load is connected to the circuit. In this condition, the output current is equal to zero. The value of Voc depends mainly on the semiconductor material, the temperature of the cell, and the level of solar irradiance.

Equation: :
$$Voc = (nkT/q) \ln((Iph/I0) + 1) \quad (1-3)$$

1.4.2 Short-Circuit Current (Isc):

The short-circuit current (Isc) is the current that flows through the photovoltaic cell when its terminals are directly connected with zero resistance. It represents the maximum current generated by the solar cell under illumination and mainly depends on solar irradiance and the effective surface area of the photovoltaic device.

Equation:
$$Isc \approx Iph \quad (1-4)$$

1.4.3 Fill Factor (FF):

The fill factor (FF) is an important parameter used to evaluate the quality and efficiency of a photovoltaic cell. It is defined as the ratio between the maximum power generated by the solar cell and the product of the open-circuit voltage and short-circuit current.

Equation:
$$FF = Pmax / (Voc \times Isc) \quad (1-5)$$

1.4.4 Maximum Power Point (MPP):

The maximum power point (MPP) corresponds to the operating point on the I-V curve where the photovoltaic cell produces the maximum electrical power. At this point, the voltage and current are denoted by Vmp and Imp respectively.

Equation:
$$Pmax = Vmp \times Imp \quad (1-6)$$

1.5 Factors Affecting Performance: The Impact of Solar Irradiance and Cell Temperature on the I-V and P-V Curves:

1.5.1 Effect of Solar Irradiance:

Solar irradiance simply means the intensity of sunlight falling on the PV cell. It is the main source of energy for the system. Unlike temperature, which mainly affects voltage, irradiance has a direct and strong effect on the current produced by the cell. When more sunlight hits the cell, more photons become available to release electrons from the semiconductor material. This creates more electron-hole pairs, which increases the flow of electric current. As a result, the short-circuit current I_{sc} rises almost in direct proportion to the increase in irradiance, and this leads to a higher maximum power output. As shown in Figure 1-8, when irradiance increases from low to high levels, the short-circuit current increases clearly, while the open-circuit voltage stays relatively unchanged (Salim & Nehal, 2025).

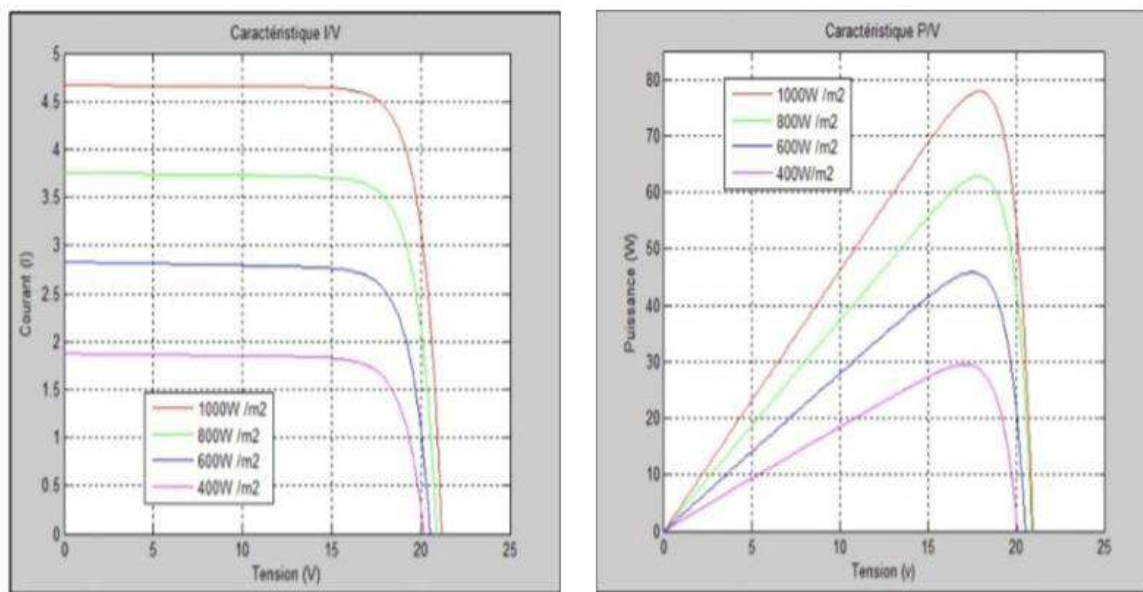


Fig.1- 8: Effect of irradiance on I-V and P-V curves (Salim & Nehal, 2025).

The relationship between irradiance and current is nearly linear. This means that any drop in sunlight, such as during cloudy weather or in the early morning, directly reduces the generated current. Under low irradiance conditions, the P-V curve becomes smaller and the maximum power point moves to lower values. Therefore, irradiance is the most important environmental factor affecting the real-time power output of a PV system (Salim & Nehal, 2025). While irradiance controls how much current the cell can produce, temperature determines how efficiently that current is delivered at a useful voltage.

1.5.2 Effect of Cell Temperature:

PV cells are made of semiconductor materials, so their electrical behavior changes noticeably with temperature. When the cell gets hot, its performance is affected in two main ways. The most significant change happens to the open-circuit voltage V_{oc} , which decreases as temperature rises. This happens because higher temperatures increase the recombination rate of charge carriers inside the material, which reduces the voltage across the cell terminals. On the other hand, the short-circuit current I_{sc} increases slightly with temperature, but this small increase is not enough to make up for the loss in voltage. As a result, the maximum power point P_{max} shifts to lower voltage values, and the overall output power decreases.

As shown in Figure 1-9 when the cell temperature rises across the typical operating range of 10°C to 50°C, the I-V curve shifts downward along the voltage axis. (Cangi, Adak, & Yilmaz, 2021; Salim & Nehal, 2025). The open-circuit voltage drops noticeably, while the short-circuit current increases only slightly.

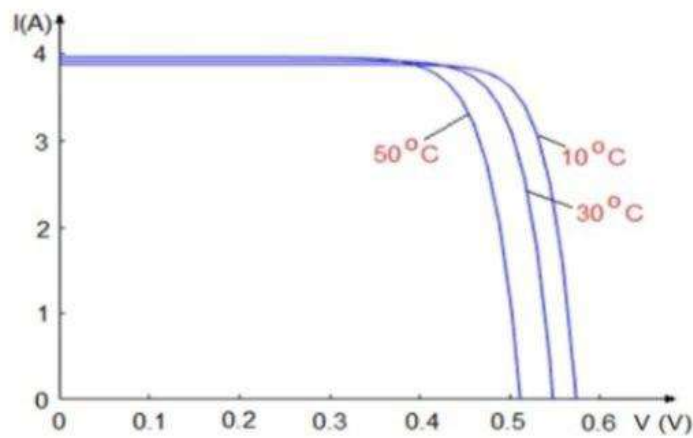


Fig.1- 9: Effect of temperature on I-V curves (Cangi et al., 2021).

Figure 1-10 also shows the P-V curves, where the maximum power point moves to lower voltage values and becomes significantly smaller as temperature increases (Cangi et al., 2021). Experimental studies have confirmed that high temperatures reduce the productivity of PV cells. In other words, the relationship between temperature and PV output is inversely proportional: the hotter the cell, the lower the power it produces (Ouédraogo et al., 2021).

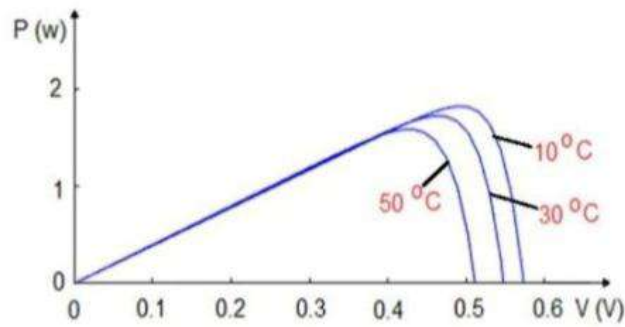


Fig. 1-10: Effect of temperature on P-V curves (Cangi et al., 2021).

Conclusion:

The above chapter has provided the essential theoretical background for the study of photovoltaic energy, covering the physical, electronic, and technological aspects associated with the process. Starting from the basic nature of solar energy and the AM1.5 standard spectrum, the discussion covered the quantum mechanics associated with photon absorption in semiconductor materials, the formation of the p-n junction and the role played in the separation of charge carriers, and the derivation of the ideal and practical solar cell equivalent circuit models involving the short-circuit current I_{sc} , the open-circuit voltage V_{oc} , the fill factor FF , and the efficiency η . The analysis of semiconductor properties has revealed that the material in question, be it monocrystalline silicon, polysilicon, compound semiconductor materials such as CdTe and CIGS, or newly introduced perovskite absorbers, plays a vital role in balancing efficiency, cost, and stability in solar cells.

The important performance characteristics discussed in the following chapters, such as the spectral response, temperature coefficient, role of series and shunt resistances, and the effect of irradiance on the I-V characteristic, form the theoretical background for the performance modeling and simulation work carried out in the subsequent chapters. The difference between Standard Test Conditions and real operating conditions, as well as the role of Nominal Operating Cell Temperature, have been highlighted as playing an important role in linking laboratory results to real world performance. In summary, therefore, the basics covered in this chapter serve to confirm that the process of photovoltaic energy conversion is a well established physical phenomenon, one which nevertheless remains full of promise in terms of scope for improvement and innovation.

**Chapter 2: Review of Characterization
Methods & Electronic Loads**

INTRODUCTION:

This chapter presents the major methods and technologies to characterize photovoltaic (PV) systems; it compares traditional manual methods and new automated approaches. It aims to develop the conceptual basis for the low-cost Arduino-based PV analyzer developed within this dissertation.

The discussion begins with a review of Data Acquisition Systems (DAQ). While commercially available DAQ solutions have very good precision, they are very costly, typically priced between \$2,000 and \$10,000 (Wetherington et al., 2020; Keysight Technologies, n.d.). As a result, most small laboratories and educational institutions in developing regions cannot afford them (Majid et al., 2022), while the Arduino platform has been identified as a "frugal innovation". The Arduino board is a microcontroller costing approximately \$10 with an additional \$20 for sensors. With regard to resolution, while commercial DAQ devices use 16-bit ADCs, Arduino uses a 10-bit ADC (0–1023), which is more than enough resolution to trace I-V curves (Arduino, n.d.).

It then examines the limitations of manual measurement of PV systems. Manually measuring PV systems using rheostats is a time-consuming process that is prone to human error and cannot capture transient changes in environmental conditions such as irradiance or temperature (Willoughby & Osinowo, 2018).

The core of this discussion focuses on electronic loads. A Metal-Oxide-Semiconductor Field Effect Transistor (MOSFET) operating in its linear region can simulate a variable resistor. Therefore, it allows precise electronic control of load resistance. Furthermore, by changing the gate voltage, the resistance between drain and source changes continuously.

Consequently, it enables fast, programmable tracing of I-V curves (Willoughby & Osinowo, 2018).

Finally, communication protocols for real-time interfacing are reviewed. The I²C protocol allows digital communication between the Arduino board and sensors, minimizing noise. Additionally, data is streamed serially over USB in CSV format, which can be visualized immediately using tools such as Excel Data Streamer (Microsoft, 2025).

Overall, these concepts show that low-cost, automated, and accurate PV analyzers are technically feasible.

2.1 Data Acquisition Systems (DAQ): Industrial vs Open-Source:

2.1.1 Introduction: The Price Gap Challenge:

Data Acquisition Systems (DAQ) are indispensable tools for measuring, recording, and analyzing electrical parameters such as voltage, current, and power. In photovoltaic (PV) applications, DAQ systems form the backbone of I-V curve tracers, enabling researchers and engineers to evaluate module performance under real operating conditions. However, a significant challenge facing educational institutions and small-scale laboratories particularly in developing regions is the prohibitively high cost of commercial PV characterization equipment. Professional-grade instruments typically range from several hundred to several thousand dollars, creating a “price gap” that limits access to modern measurement tools and hinders hands-on learning in renewable energy engineering.

This section reviews the landscape of commercial PV analyzers, highlights the cost barrier, and introduces the Arduino platform as a frugal engineering alternative.

2.1.2 High-End Commercial PV Analyzers: Four Representative Examples:

The market offers several professional PV analyzers designed for system commissioning, performance monitoring, and fault diagnosis. The following four examples illustrate the diversity in price, capability, and form factor, as well as the overall high cost of entry.

Example 1: HT Instruments I-V400w – Handheld Field Tester:

HT Instruments is an established Italian manufacturer of electrical and solar testing equipment. The I-V400w is a portable, handheld I-V curve tracer designed for field use on PV modules and strings. According to the manufacturer's specifications, the instrument can measure output voltage up to 1000 V DC and output current up to 15 A DC, making it suitable for both individual modules and complete strings (HT Instruments, n.d.). Key features include:

- I-V curve measurement: 128 points per curve in Standard or Capacitive mode (HT Instruments, n.d.)
- Key parameters: Measures Voc, Isc, Pmax, Vmpp, Impp, Fill Factor, and series resistance (HT Instruments, n.d.)
- Environmental sensors: Includes reference cell for solar irradiation measurement (W/m^2) and PT1000 probe for temperature measurement (HT Instruments, n.d.)

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- STC conversion: Automatically compares measured data to Standard Test Conditions (1000 W/m², 25°C) (HT Instruments, n.d.)
- Database: Internal memory for up to 30 module types, upgradeable to 30,000 via software (HT Instruments, n.d.)
- Connectivity: Optical/USB port for PC connection plus Wi-Fi for wireless data transfer (HT Instruments, n.d.)
- Additional features: Mechanical inclinometer, 4-terminal measuring method, graphical display of I-V characteristics, and on-line help (HT Instruments, n.d.)

The I-V400w also allows quick tests (IVCK) to measure Voc and Isc even without adequate irradiation conditions (HT Instruments, n.d.). The acquired data can be transferred to a PC using the TOPVIEW management software, and the internal module database can be updated by the user either through the software or directly via the instrument's interface (HT Instruments, n.d.). The I-V400w is priced at approximately **\$4,250 USD** (HT Instruments, n.d.).



Figure 2.1. HT Instruments I-V400w handheld I-V curve tracer for PV field testing
(Source: HT Instruments).

Example 2: Solmetric PVA-1500HE – High-Efficiency Bench-top Analyzer with Wireless Sensor:

Solmetric, now part of Fluke Corporation, is a recognized leader in PV performance analysis tools. The PVA-1500HE (High Efficiency) is a high-end I-V curve tracer specifically designed to accurately measure high-efficiency PV modules (efficiency $\geq 19\%$) and large

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strings, which pose measurement challenges due to their high capacitance (Solmetric, n.d.). According to the manufacturer, the "HE" designation indicates that this is the only curve tracer capable of measuring high-efficiency strings up to a full 30A (Solmetric, n.d.). Key specifications include:

- Voltage range: 20 to 1500 V DC
- Current range: Up to 30 A DC (unlike standard models limited to 10 A for high-efficiency modules)
- I-V trace points: 100 or 500 points per curve, selectable
- Sweep duration: 0.05 to 2 seconds (typically 0.2 seconds for strings)
- Measurement accuracy : $\pm 0.5\% \pm 0.25$ V (voltage), $\pm 0.5\% \pm 40$ mA (current)
- Communication: WiFi interface to tablet or laptop (user-supplied)
- Wireless sensor: Sol Sensor for irradiance ($\pm 2\%$ accuracy), temperature (two external thermocouple inputs), and module tilt; 300 ft wireless range
- Thermal capacity: Unlimited sweeps in normal conditions; up to 330 sweeps at 45°C ambient with 9 s sweep-to-sweep delay
- Additional features: SmartStamp temperature blending, automatic STC translation, Go/NoGo testing, and I-V Data Analysis Tool for professional report generation

The PVA-1500HE can commission approximately 1 MW of PV capacity in less than 2 hours even in hot environments exceeding 43 °C ambient. The system is also capable of measuring traditional PV technologies with equal accuracy. The kit includes the I-V curve tracer, SolSensor, Windows software, and all accessories (computer or tablet not included). The Solmetric PVA-1500HE is priced at approximately **\$15,995.00 USD** (Solmetric, n.d.).



Figure 2.2. Solmetric PVA-1500HE high-efficiency PV analyzer kit with wireless SolSensor.

Example 3: Seaward PV200 – Compact Handheld Tester with Reporting Software:

Seaward Electronic Ltd., a British manufacturer of electrical test equipment, offers the PV200, a compact, handheld solar PV tester that combines I-V curve tracing with electrical safety commissioning tests in a single portable device (Seaward, n.d.). According to the manufacturer, the PV200 is a “compact and cost effective I-V curve tracer” that uses simple push-button operation, making it an efficient and versatile tester for PV systems (Seaward, n.d.). Key specifications include:

- Voltage measurement: Up to 1000 V DC (open circuit and maximum power point voltage)
- Current measurement: Up to 15 A DC (short circuit and MPP current) with external AC/DC clamp (0.5–40 A)
- Fill factor: Automatically calculated
- Insulation resistance test: 250/500/1000 V (eliminates need for separate insulation tester)
- Continuity testing: Earth (ground) continuity with test lead null
- Data storage: Memory for up to 999 records, USB download to PC
- Communication: NFC for instant data transfer using the PVMobile app (iOS/Android)
- Wireless connectivity: Optional Solar Survey 200R irradiance meter (irradiance, ambient temperature, module temperature) for real-time environmental data
- Reporting software: SolarCert software included for data analysis, STC comparison, fill factor calculation, and professional report generation
- Display: High-contrast display clearly visible in direct sunlight
- Applications: Tests individual PV modules or complete strings

The PV200 Complete Kit includes the tester, Solar Survey 200R irradiance meter with mounting bracket, SolarCert reporting software, AC/DC current clamp, test leads with MC4 adaptors, combiner box probes, rugged carry bag, calibration certificates, and a 2 year warranty. The PV200 is priced approximately at **\$2,000 USD** (based on international pricing, with variations by region) (Seaward, n.d.).



Figure 2.3. Seaward PV200 compact handheld I-V curve tracer with wireless irradiance meter (Source: Seaward Electronic Ltd.).

Example 4: EKO Instruments MP-180 – High-Precision Laboratory Benchtop Tracer:

EKO Instruments, a Japanese manufacturer of high-precision optical and solar measurement instruments, offers the MP-180, a laboratory-grade I-V tracer designed for photovoltaic cell research, development, and quality inspection (EKO Instruments, n.d.). Unlike field-portable testers, the MP-180 is a benchtop instrument intended for use with solar simulators in controlled laboratory environments (EKO Instruments, n.d.). Key specifications include:

- Voltage range: 0 to 20 V DC (auto-ranging with selectable 2V or 20V ranges)
- Current range: 0 to 20 A DC (auto-ranging from 20 μ A to 20 A across eight ranges)
- Voltage resolution: 0.24 to 2.4 μ V (depending on range)
- Current resolution: 0.24 pA (picoampere) at the lowest range (20 μ A), offering exceptionally high resolution for low-current measurements
- Measurement accuracy: $\pm 0.1\%$ (voltage and current)
- Number of data points: 4096 points per I-V curve
- Sweep time: Adjustable from 0.005 to 300 seconds, offering exceptional flexibility
- Power range: Up to 100 W (20 V $\times$ 20 A), suitable for individual cells and small modules
- Communication : RS-232, USB, LAN (EKO Instruments, n.d.)
- Trigger function: Built-in trigger to synchronize with pulsed solar simulators (flash simulators) and shutter control for continuous simulators (EKO Instruments, n.d.)

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- Optional switching units: For multi-channel measurements (multiple PV cells, pyranometers, temperature sensors)
- Power supply: 100–240 VAC, 200 W
- Dimensions: $450 \times 459 \times 133$ mm, 9 kg (benchtop form factor)
- Operating temperature: 0–40 °C
- PC software: For data visualization, data management, and calculation of cell parameters (R_s , R_{sh} , etc.)

The MP-180 is unique among the four examples because it is not a field portable instrument but a laboratory research tool designed to test individual PV cells under controlled illumination (EKO Instruments, n.d.). Its ultra-wide current range (20 μ A to 20 A) allows it to measure everything from small research-scale cells to full-size industrial cells (EKO Instruments, n.d.). Prices for the MP-180 are typically available upon request from EKO Instruments, though similar precision laboratory I-V tracers generally range from approximately **\$10,000 to \$20,000 USD** (EKO Instruments, n.d.).



Figure 2.4. EKO Instruments MP-180 high-precision laboratory benchtop I-V tracer for PV cell research.

2.1.3 The Price Gap:

The four examples above confirm a clear and substantial price barrier, Commercial PV Analyzer Approximate Price (USD) Primary Application:

- Seaward PV200 ≈\$2,000 Compact handheld field tester (Seaward, n.d.)
- HT Instruments I-V400w \$4,250 Handheld field tester with database management (HT Instruments, n.d.)
- EKO Instruments MP-180 ≈\$10,000–20,000 Laboratory benchtop for cell research (EKO Instruments, n.d.)
- Solmetric PVA-1500HE \$15,995 High-efficiency string analyzer (Solmetric, n.d.)

These prices place professional PV analyzers out of reach for many small laboratories, vocational training centres, and universities in developing countries. The most affordable commercial unit among those surveyed (Seaward PV200 at ≈\$2,000) is still approximately 40 times more expensive than a complete Arduino-based DAQ system. The top-end units (\$16,000) are over 300 times more expensive. Moreover, the costs often do not include optional accessories (e.g., additional test leads, wireless adapters, software licenses) or annual calibration fees.

Consequently, students and researchers in resource-constrained settings are frequently limited to theoretical instruction rather than hands-on experimentation, slowing innovation and skill development. This price disparity has motivated the development of open-source, microcontroller-based alternatives that can provide sufficient measurement accuracy for educational and research applications at a fraction of the cost.

2.1.4 Arduino as a Frugal Innovation: Low-Cost DAQ for PV Characterization:

The concept of frugal engineering achieving essential functionality with minimal resources provides a compelling alternative. The Arduino platform embodies this philosophy. An Arduino Mega 2560 microcontroller board costs approximately \$15–\$20 (Arduino, n.d.). The Mega 2560 is based on the ATmega2560 and features 54 digital input/output pins (of which 15 can be used as PWM outputs), 16 analog inputs, 4 hardware serial ports (UARTs), a 16 MHz crystal oscillator, and a USB connection (Arduino, n.d.).

When combined with a precision current/voltage sensor such as the INA219 (≈\$3–\$5), which will be detailed in Chapter 3, the system utilizes efficient communication protocols like I2C (to be discussed in Section 2.4.2). This integrated setup allows the total hardware cost for a basic PV characterization system to remain well under \$50 (Texas Instruments, n.d.).

Despite the low cost, such a system can deliver surprisingly accurate results. Pachauri et al. (2021) developed an Arduino-assisted data acquisition system for solar PV array

characterization under partial shading conditions. Their system achieved percentage errors as low as 0.48%, 1.95%, and 1.37% under different shading cases when compared with MATLAB/Simulink simulations (Pachauri et al., 2021). More importantly, the system was economical and minimized the testing period relative to traditional approaches (Pachauri et al., 2021).

Similarly, Moreno et al. (2020) demonstrated that a low-cost, Arduino-based DAQ system could achieve reliable acquisition rates suitable for high-frequency and real-time applications, proving that open-source hardware can be adapted for demanding use cases through careful firmware design (Moreno et al., 2020).

2.1.5 ADC Resolution: 10-bit vs 16-bit and Why It Matters:

The analog-to-digital converter (ADC) is a critical component in any DAQ system because it converts continuous analog signals (e.g., sensor voltages) into discrete digital values. The resolution of an ADC, expressed in bits, determines how many discrete steps are available over the input range.

- A 10-bit ADC (standard on Arduino boards) divides a 0–5 V input into $2^{10} = 1,024$ steps, yielding a resolution of approximately 4.88 mV per step.
- A 16-bit ADC (common on commercial systems) divides the same input into $2^{16} = 65,536$ steps, offering a resolution of approximately 0.076 mV per step more than 60 times finer.

For many engineering applications requiring very small signal detection, the higher resolution of a 16-bit ADC is essential. However, for PV module characterization (I-V and P-V curve tracing), the electrical changes are relatively large. An 80 W PV module typically produces an open-circuit voltage of approximately 22 V and a short-circuit current of about 5 A. Using a simple voltage divider to scale the 0–22 V range down to the Arduino's 0–5 V input, the 10-bit resolution of 4.88 mV translates to approximately 0.022 V measurement uncertainty at the PV terminals. This level of precision is more than adequate for accurately tracing I-V curves, locating the maximum power point (MPP), and calculating key parameters such as fill factor (FF) and efficiency (Pachauri et al., 2021).

Thus, while a 16-bit ADC offers higher precision, the additional cost and complexity are not justified for the specific application of educational and research-grade PV characterization. The Arduino's 10-bit ADC provides a cost-effective trade-off between accuracy and affordability, aligning perfectly with the frugal engineering approach adopted in

this thesis. The following chapter will build on these trade-offs to select specific hardware components for this frugal DAQ system.

2.2 Manual vs Automated Measurement: Limitations of the Rheostat Method and Alternative Topologies:

2.2.1 Introduction to I-V Curve Tracer Topologies:

Before examining the limitations of the manual rheostat method, it is useful to understand the four main topologies of I-V curve tracers reported in the literature. According to the comprehensive review by Morales-Aragonés et al. (2021), I-V tracers can be classified according to the load type used to sweep the operating point of the PV module. These topologies include: (1) variable resistor tracers (rheostats), (2) capacitive load tracers, (3) electronic load tracers (using MOSFETs or transistors), and (4) DC-DC converter-based tracers. Each topology presents distinct trade-offs in terms of cost, speed, accuracy, complexity, and suitability for different power levels. The following subsections describe each topology and compare their characteristics, with particular emphasis on the electronic load approach based on MOSFETs operating in the linear region which forms the foundation of the low-cost Arduino-based PV analyzer proposed in this thesis (Morales-Aragonés et al., 2021).

2.2.2 Topology 1: Variable Resistor Tracer (Rheostat Method):

The traditional and conceptually simplest approach is the variable resistor tracer, commonly implemented using a rheostat—a manually adjustable wire-wound resistor. In this method, the operator physically rotates a knob or slider to change the resistance connected across the PV module terminals, while simultaneously reading the corresponding current and voltage values from analog or digital meters (Morales-Aragonés et al., 2021). The resistance range must ideally cover from zero (short-circuit condition) to infinity (open-circuit condition) to capture the complete I-V curve. A typical rheostat used in such manual I- V curve tracing is shown in Figure 2.5:

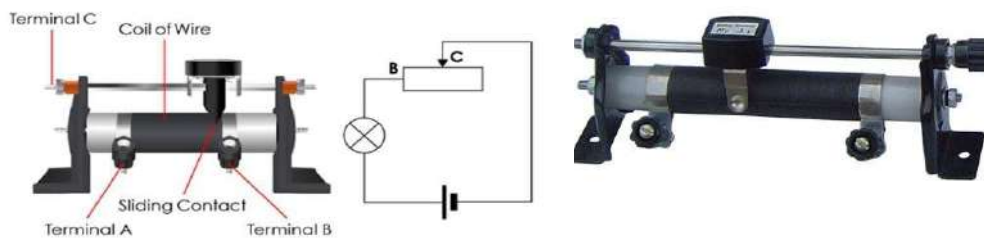


Fig. 2.5. Rheostat manual (variable resistor).

Despite its conceptual simplicity and low component cost, the rheostat method suffers from three fundamental limitations that compromise its accuracy and practicality for modern PV characterization.

Time-Consuming Nature: Each data point on the I-V curve requires a manual adjustment of the rheostat followed by manual reading and recording of current and voltage values. Completing a full I-V curve with adequate resolution (e.g., 50–100 points) typically takes several minutes. This slowness is critical because environmental conditions such as solar irradiance and cell temperature change continuously during the measurement period. As reviewed by Morales-Aragonés et al. (2021), the manual change of resistors takes considerable time, so solar radiation and thermal conditions may change while the test is carried out, leading to distorted and non-uniform I-V curves. The importance of fast measurement has been further emphasized by Schönau et al. (2024), who noted that shorter measurement durations minimize errors caused by fluctuations in irradiance during data acquisition.

Human Error and Poor Repeatability: Manual readings of analog instruments are prone to parallax errors (incorrect viewing angles), and manual recording of values introduces transcription mistakes. Moreover, different operators may adjust the rheostat at different rates or stop at slightly different resistance values, leading to inconsistent and non-repeatable results. According to Morales-Aragonés et al. (2021), the precision of the rheostat method is not high because it is susceptible to human error, which directly impacts the quality of extracted electrical parameters such as maximum power point (P_{max}), fill factor (FF), and series resistance (R_s). These errors accumulate across the I-V curve, reducing confidence in the characterization results.

Lack of Transient Data Capture: PV modules are constantly exposed to changing environmental conditions a passing cloud can reduce irradiance by 50% in a few seconds, and wind gusts can change cell temperature rapidly. Because the manual rheostat method is slow, it effectively averages over these variations rather than capturing the I-V curve at a single, well-defined operating point.

The resulting curve is therefore distorted and may not represent the actual performance of the module under any specific condition. Morales-Aragonés et al. (2021) clearly state that since solar radiation and temperature vary while the test is carried out, the manually measured I-V curve does not have uniformity. Consequently, this method is only suitable for low-power

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PV generators (<1 kW), and high-power rheostats are rarely available in the market, further limiting its practicality (Morales-Aragonés et al., 2021).

Despite the widespread use of conventional rheostats as fundamental tools for manual resistance control and current adjustment within university laboratories, practical application reveals clear limitations in their operational efficiency. Experimentally, a single rheostat unit is insufficient to cover the required range or satisfy precise measurement needs, necessitating the combination of four units connected in series/parallel to function as an integrated system. This reliance on linking multiple manual units increases the complexity of the circuit wiring and renders the resistance adjustment fragmented and lacking automated smoothness, directly impacting the continuity and accuracy required in advanced characterization and measurement experiments.

This formulation perfectly explains the exact setup shown in your laboratory photos without adding any unnecessary details.

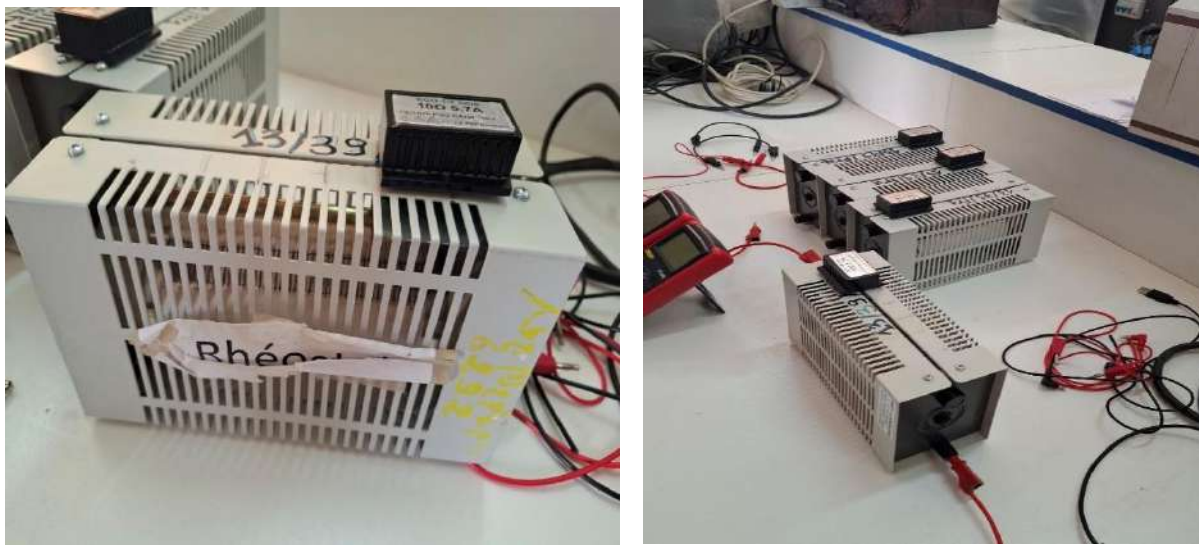


Figure 2.6: Experimental setup using four series/parallel connected conventional rheostats to expand power capacity for manual I-V curve tracing.

To overcome the human errors, low resolution, and lack of continuity inherent in manual rheostats, commercial testing systems have evolved toward integrated units such as the "DC-Load Module" (e.g., systems manufactured by Edibon). These specialized laboratory instruments function as automated, electronically controlled dynamic loads, providing high precision, excellent repeatability, and stable data acquisition across the entire I-V curve.

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However, despite their high operational efficiency and advanced features, these commercial modules are remarkably expensive and cost-prohibitive for many universities, particularly in developing nations. Consequently, it is economically impractical to equip every student laboratory with such high-end instruments, which severely limits students' hands-on access to modern photovoltaic characterization. This financial barrier emphasizes the critical need for developing low-cost, open-source automated alternatives using microcontrollers and solid-state electronics.



Figure 2.7: DC Load Module.

2.2.3 Topology 2: Capacitive Load Tracer:

An alternative approach to avoid the slowness of manual resistance adjustment is the capacitive load tracer. In this topology, a capacitor (or a bank of capacitors) is connected as the load across the PV module. The operating principle is straightforward: when the capacitor is initially discharged, it behaves as a short circuit (zero voltage, maximum current); as it charges, its voltage rises, tracing the I-V curve from the short-circuit point (I_{sc}) toward the open-circuit point (V_{oc}). Once fully charged, the capacitor is discharged through resistors to prepare for the next measurement cycle (Morales-Aragón et al., 2021).

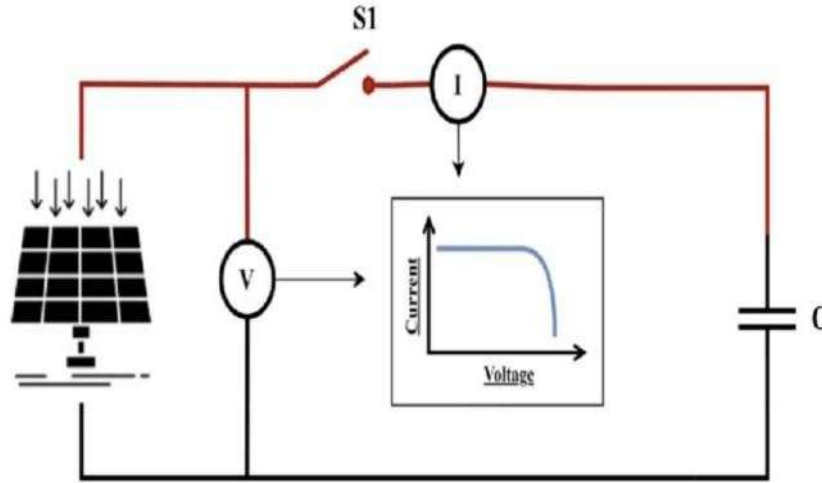


Fig. 2.8. Basic circuit diagram of a capacitive load tracer for I-V curve measurement (Londoño et al., 2022).

The primary advantage of the capacitive load method is speed. The charging of the capacitor occurs automatically once the measurement cycle is initiated, completing the full I-V sweep in milliseconds to seconds depending on the capacitor size and module power. This rapid acquisition minimizes errors due to changing irradiance and temperature conditions (Morales-Aragonés et al., 2021). Additionally, the capacitive load approach can be designed for high-voltage and high-power PV modules up to several kilowatts.

However, capacitive load tracers have several disadvantages. The measured I-V curve is influenced by the capacitor's equivalent series resistance (ESR) and the charging dynamics, which can introduce distortions. The method also does not naturally allow arbitrary scanning speeds; the sweep is determined by the RC time constant. Furthermore, the capacitor bank can be bulky and costly for high-power applications (Morales-Aragonés et al., 2021). Erkaya et al. (2016) demonstrated an improved capacitive load design using MOSFET switches to control the charging and discharging cycles, achieving faster reset times and better repeatability for on-site PV characterization. As further noted by Londoño et al. (2022), capacitive tracers can produce incomplete I-V curves, particularly in the I_{sc} and V_{oc} regions, due to transient switching effects, capacitance sizing, and variations in irradiance levels during outdoor tests (Londoño et al., 2022).

2.2.4 Topology 3: Electronic Load Tracer (MOSFET-Based):

The electronic load tracer represents a significant advancement over both rheostat and capacitive methods. In this topology, a power MOSFET (Metal-Oxide-Semiconductor Field-Effect Transistor) is used as the variable load. By applying a controlled voltage to the MOSFET's gate terminal, the resistance between its drain and source terminals can be varied continuously and electronically. When operated in its linear (ohmic) region, the MOSFET behaves as a voltage-controlled resistor, allowing precise and fast adjustment of the load current drawn from the PV module (Morales-Aragonés et al., 2021; Willoughby & Osinowo, 2018).

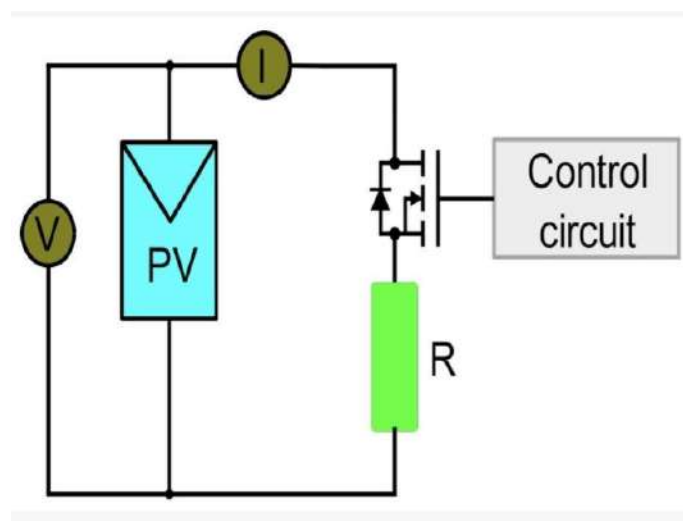


Fig. 2.9. Simplified circuit diagram of a MOSFET-based electronic load tracer for I-V curve measurement (Morales-Aragonés et al., 2021).

The electronic load approach offers multiple advantages:

- **Speed and Automation:** The gate voltage can be swept electronically using a microcontroller-generated PWM signal, enabling complete I-V curves to be acquired in seconds or even milliseconds. This rapid acquisition ensures that all measured points are captured under essentially constant irradiance and temperature conditions, overcoming the "lack of transient data" limitation of rheostat methods (Willoughby & Osinowo, 2018).
- **High Repeatability:** Because the entire sweep is controlled by software, the same procedure is followed exactly for every measurement, eliminating operator-to-operator variability and manual recording errors. This results in excellent measurement repeatability (Machado et al., 2025).
- **Low Cost:** Power MOSFETs are widely available at low cost. When combined with an open-source microcontroller platform such as Arduino, the total hardware cost

for a complete I-V curve tracer can be reduced to a fraction of the price of commercial instruments (De Riso et al., 2024).

- Flexibility: The sweep rate, number of points, and current/voltage ranges can be easily modified in software, allowing the same hardware to be adapted to different PV modules under various conditions.

The main disadvantage of the electronic load topology is thermal management. Operating a MOSFET in its linear region dissipates significant power, requiring adequate heatsinking and possibly forced-air cooling to prevent overheating and thermal runaway. Nonetheless, with proper heatsink design, this limitation is manageable for modules up to several hundred watts (Morales-Aragonés et al., 2021).

The electronic load method is the topology adopted in this thesis. Specifically, the proposed PV analyzer uses an IRLZ44N logic-level N-channel MOSFET driven by an Arduino Mega 2560 through an RC low-pass filtered PWM signal. The INA219 sensor provides accurate current and voltage measurements via the I²C bus. This combination offers a cost-effective, accurate, and reproducible solution for characterizing 80 W PV modules while addressing all three limitations of the manual rheostat method (Willoughby & Osinowo, 2018; Machado et al., 2025).

2.2.5 Topology 4: DC-DC Converter-Based Tracer:

A more advanced topology uses a DC-DC converter as the programmable load. By adjusting the duty cycle of the converter's switching transistor, the equivalent input resistance seen by the PV module can be varied, sweeping the operating point across the I-V curve (Morales-Aragonés et al., 2021).

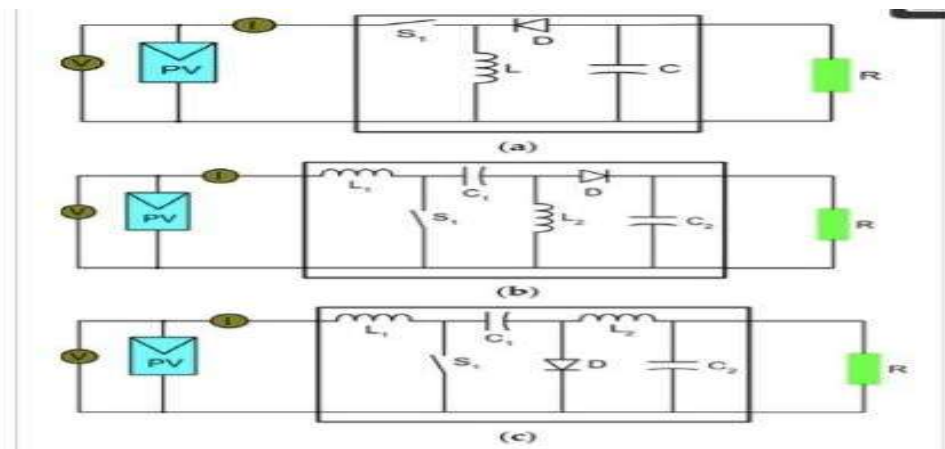


Fig. 2.10. Derived DC-DC converters for I-V curve tracing: (a) Buck-boost; (b) SEPIC; (c) Cuk (Morales-Aragonés et al., 2021).

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The main advantage of DC-DC converter-based tracers is that they can be designed to operate efficiently over a wide voltage and current range, often with higher power handling capability than a single MOSFET. They also enable energy recovery, since the power drawn from the PV module can be delivered to a storage battery or resistive load rather than being completely dissipated as heat. This makes the approach attractive for high-power applications and continuous operation.

However, DC-DC converter topologies introduce additional complexity. The measurement accuracy depends on the converter's dynamics, switching ripple, and the control loop bandwidth. Proper filtering and synchronization are required to avoid distortion of the I-V curve. Moreover, designing and programming a stable closed-loop converter adds to development time and cost. For low-power, cost-sensitive educational applications, the added complexity of a DC-DC converter is often not justified (Morales-Aragónés et al., 2021).

2.2.6 Comparative Summary of Topologies and the Superiority of Electronic Load Method:

Topology	Speed	Accuracy	Cost	Complexity	Suitable Power Level
Rheostat (variable Resistor)	Very slow	Low (affected by human error and irradiance changes)	Low	Very Low	Low (<1 KW)
Capacitive Load	Fast	Moderate (ESR and charging dynamics can distort curve)	Moderate	Moderate	Up to several KW

Electronic Load (MOSFET)	Fast to very fast	High (software – controlled, repeatable)	Low (with Arduino platform)	Moderate	Low to moderate (up to few hundred watts)
DC – DC Converter	Moderate to fast	Moderate to high (depends on converter dynamics)	Moderate to high	High	High (KW scale)

Table 2.1 Comparison of I-V curve tracer topologies: rheostat, capacitive load, electronic load, and DC-DC converter.

From the comparison presented above, the electronic load (MOSFET) topology emerges as the most suitable choice for a low-cost, educational PV characterization system targeting an 80 W module. It combines the advantages of fast, automated, and repeatable measurements with low component cost and moderate circuit complexity. This topology directly overcomes all three limitations of the manual rheostat method: time consumption, human error, and inability to capture transient data while remaining accessible to small laboratories and educational institutions in developing regions (De Riso et al., 2024; Morales-Aragón et al., 2021).

The viability and accuracy of such automated systems have been demonstrated in recent research. Willoughby and Osinowo (2018) developed an Arduino-based electronic load I-V curve tracer that successfully characterized PV modules under outdoor conditions. De Riso et al. (2024) developed a low-cost, microcontroller-based I-V tracer with a mean relative error of less than 3%, closely matching theoretical values. Their system achieved even distribution of measurement points along the I-V curve and enabled in-situ and on-line measurement without interrupting string power generation (De Riso et al., 2024). Machado et al. (2025) further demonstrated an automated load-switching I-V curve tracer with high repeatability and low cost. These studies confirm that automated electronic load systems overcome all three limitations of the manual rheostat method while offering additional advantages such as portability, low cost, and real-time monitoring capabilities.

2.3 Principles of Electronic Loads:

2.3.1 Operating Principle of a MOSFET as a Variable Resistor:

The basic principle behind an electronic load, which is a controlled resistor circuit, is that it makes possible for us to control or adjust electronically the amount of current we draw from a power source (like a PV cell), instead of having to do so with manual adjustments. The MOSFET functions as the "water tap" on our analogy; i.e., the gate voltage represents the "tap" by which we regulate how much water (or current) passes through the "pipe" (the channel).

To create the complete, I-V curve of a PV cell, one needs to vary the load resistance continuously from zero (i.e., short-circuit) to infinite resistance (i.e., open-circuit). The ability to quickly, precisely and programmatically adjust the load resistance provides significant advantages over using traditional methods, namely adjusting a variable resistor (rheostat) manually. (Rashid, 2014, Chapter 4)

The heart of the electronic load in this project will be a Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) which has three terminals. Those terminals have been designated by their respective names as follows; Gate (G), Drain (D) and Source (S). Here we will configure the MOSFET so it acts like a Voltage Controlled Resistor. As a voltage is applied to the Gate terminal with reference to S, then an electrical field is generated that influences the conductivity of the semiconductor between D and S. Also, if you vary the gate voltage, you may control the continuous adjustment of resistance between D and S. When the Gate voltage is 0 V, there will be little to no current passing through since the MOSFET presents a very high resistance (virtually an open circuit). If the Gate voltage reaches its maximum possible value (in most cases 5V for logic level MOSFETs), the MOSFET will virtually present a negligible resistance (a virtual short circuit) and allow the maximum amount of current to pass. For any Gate voltage between 0V and 5V, the MOSFET will offer some form of resistance (Rashid, 2014).

To make this type of behavior usable as a load, it will have to operate in its linear or ohmic region. It operates in the linear/ohmic region when drain-source voltage is low compared with gate voltage. The MOSFET acts like an actual resistor where its resistance value is exactly determined by the applied gate voltage. Its linear characteristics make MOSFETs very well suited for use as electronic loads in PV characterization systems (Rashid, 2014; Texas Instruments, 2019).

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Mathematically, when a MOSFET operates in the linear (ohmic) region, the drain current I_D is given by: (Rashid, 2014, Chapter 4)

$$I_D = k_n \left[(V_{GS} - V_{th})V_{DS} - \frac{V_{DS}^2}{2} \right] \quad (2-1)$$

where k_n is the transconductance parameter (dependent on the MOSFET's geometry and carrier mobility), V_{GS} is the gate-to-source voltage, V_{th} is the threshold voltage, and V_{DS} is the drain-to-source voltage. For very small V_{DS} (typically $V_{DS} \ll 2(V_{GS} - V_{th})$), the quadratic term becomes negligible, and the relationship simplifies to:

$$I_D \approx k_n (V_{GS} - V_{th})V_{DS} \quad (2-2)$$

This simplified form shows that the MOSFET behaves like a linear resistor with an effective resistance of:

$$R_{DS} \approx \frac{1}{k_n (V_{GS} - V_{th})} \quad (2-3)$$

Thus, by controlling V_{GS} , the Arduino can continuously adjust the resistance R_{DS} electronically. (Rashid, 2014, Chapter 4)

Table 2.2 summarizes the three operating regions of a MOSFET (based on Rashid, 2014, Section 4.3.1)

Behavior	Condition	Region
Open circuit (OFF)	$V_{th} < V_{GS}$	Cut-off
Voltage-controlled resistor	$V_{GS} > V_{th}$, V_{DS} small	Linear (Ohmic)
Constant current source	$V_{GS} > V_{th}$, V_{DS} large	Saturation

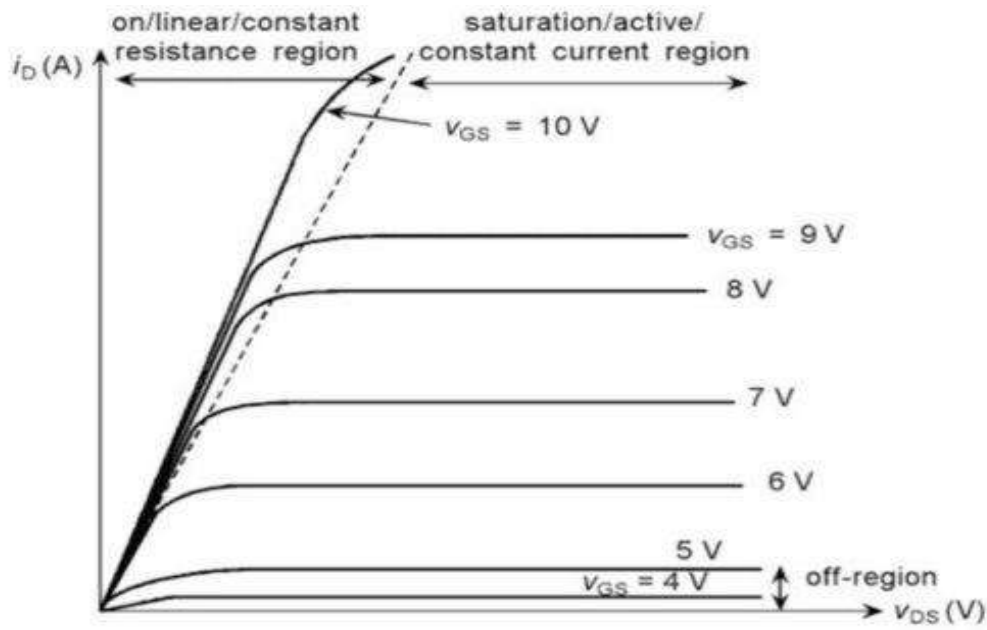


Figure 2.11: Typical output characteristics of a power MOSFET showing linear and saturation regions.

2.3.2 Arduino-Based Control of the Electronic Load:

The Arduino microcontroller generates a PWM (Pulse Width Modulation) signal at one of the Output Pins. The Digital Signal produced by the Arduino switches at a rapid rate between 0 volts and 5 volts; it is then converted into a variable analog signal ranging from 0 volts to 5 volts using a simple low pass filter consisting of a resistor-capacitor combination.

The relationship between the PWM duty cycle (D) and the resulting gate voltage V_{GS} after the low-pass filter is given by:

$$V_{GS} = D \times V_{ref} \quad (2-4)$$

where D is the duty cycle (ranging from 0 to 1) and $V_{ref} = 5V$ is the Arduino's reference voltage. The Arduino provides 256 discrete steps (0-255), giving a voltage resolution of approximately 19.5 mV per step.

This Analog Voltage is then connected to the Gate of the MOSFET, assuming that a logic-level MOSFET was utilized that requires only a 5 Volt Gate Signal to turn on completely. For higher power MOSFETs requiring greater than 5 Volts to turn-on, a separate Gate Driver Circuit will be required (International Rectifier, 2015).

The Arduino can determine a specific gate voltage to a degree as small as possible by sending PWM (pulse width modulation) signals (ranging from 0-255) to the digital output pin of the controller. It then determines which load resistance corresponds to the same Gate voltage value. The controller uses external sensing devices to read the new values for current and voltage on the PV panel. The Arduino performs data acquisition at high speed. While the microcontroller can capture data points in microseconds, the total I-V sweep duration is typically set between 100 and 200 milliseconds. This specific timeframe is designed to account for the settling time of the RC low-pass filter, ensuring that the gate voltage has stabilized at each step for maximum measurement accuracy.

The settling time of an RC filter is approximately 5τ , where $\tau = R \times C$ is the time constant. For example, with $R = 1\text{k}\Omega$ and $C = 10\mu\text{F}$, $\tau = 10\text{ms}$ and the settling time is 50ms, which justifies the 100-200 ms sweep duration used in this system.

Despite this deliberate delay for precision, the process remains significantly faster than manual methods, allowing the system to capture the PV panel's characteristics under stable environmental conditions and effectively eliminate human error.

The above characteristics make an automated PV Analyzer feasible at a reasonable cost, and thus is the basis of the low-cost PV Analyzer.

2.4 Communication and Real-Time Interfacing:

2.4.1 Introduction to Real-Time Communication Systems:

Modern photovoltaic characterization systems require efficient communication interfaces capable of transferring measurement data accurately and continuously between sensors, controllers, and host computers. Real-time interfacing ensures that electrical parameters such as voltage, current, and power are acquired, processed, and visualized without significant delay, which is essential for dynamic analysis and performance monitoring of PV modules under changing environmental conditions (Horowitz & Hill, 2015).

2.4.2 I²C Protocol for Sensor Integration:

One of the most widely adopted communication standards in embedded measurement systems is the Inter-Integrated Circuit (I²C) protocol. Developed for short-distance communication between integrated circuits, I²C enables a microcontroller such as Arduino to communicate digitally with current and voltage sensors using only two data lines: Serial Data (SDA) and Serial Clock (SCL). This approach minimizes wiring complexity, reduces analog

noise susceptibility, and improves measurement reliability in laboratory environments (NXP Semiconductors, 2021).

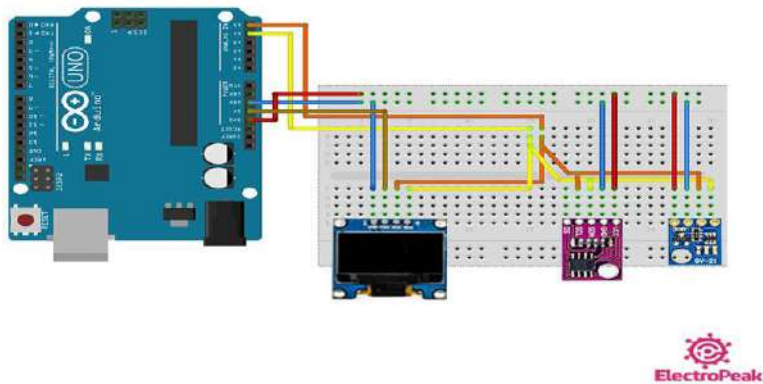


Fig 2.12: Hardware wiring diagram of an I2C-based monitoring system using Arduino.

2.4.3 Serial Data Streaming via USB/UART:

Another essential aspect of real-time interfacing is serial data streaming through USB or UART communication. In this method, the microcontroller transmits measured values in structured formats such as Comma-Separated Values (CSV), allowing direct reception by a computer for storage or processing. Serial communication is particularly advantageous because of its simplicity, wide compatibility, and ability to support continuous monitoring applications at relatively low cost (Banzi & Shiloh, 2022).

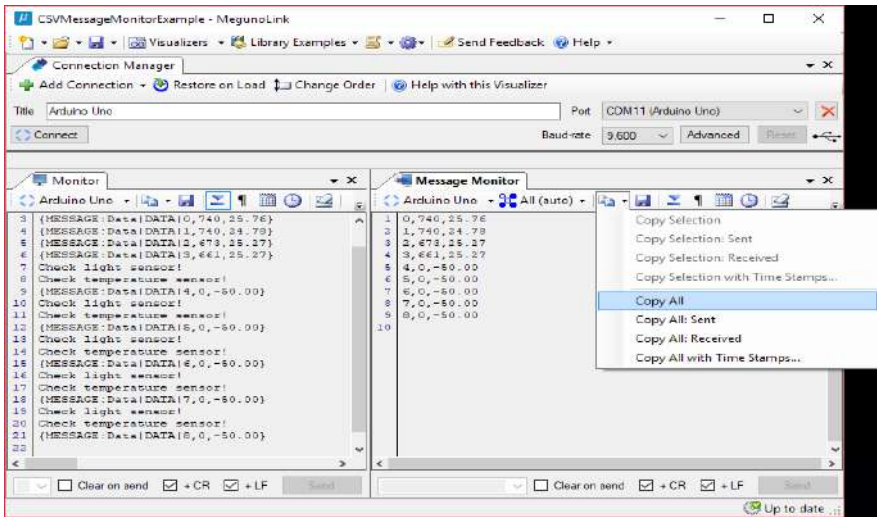


Fig 2.13: Real-time data monitoring and CSV logging using the MegunoLink interface.

2.4.4 visualizing I-V and P-V curves in real time (El Hammoumi et al., 2018).

To further enhance usability, modern software tools such as Microsoft Excel Data Streamer, MATLAB, or Python-based dashboards can receive serial data buffers and display them instantly in graphical form. This capability allows researchers to observe current-voltage (I-V) and power-voltage (P-V) curves in real time, facilitating immediate interpretation of photovoltaic performance and rapid detection of anomalies during experiments (El Hammoumi et al. Renewables (2018) 5 :3).

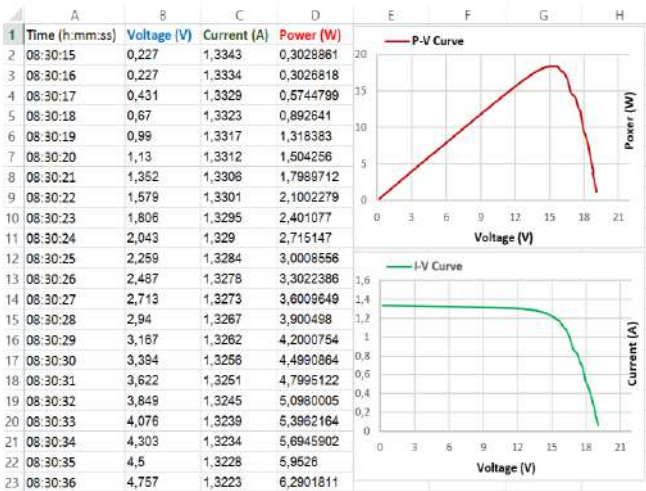


Fig 2.14: Experimental data analysis showing P-V and I-V characteristic curves.

2.4.5 Importance of Communication Technologies in PV Monitoring Systems:

Therefore, communication protocols and real-time interfacing technologies constitute a fundamental component of low-cost automated PV characterization systems, bridging the gap between hardware measurements and intelligent data analysis. Their integration significantly improves experimental efficiency, accuracy, and accessibility for educational and research laboratories.

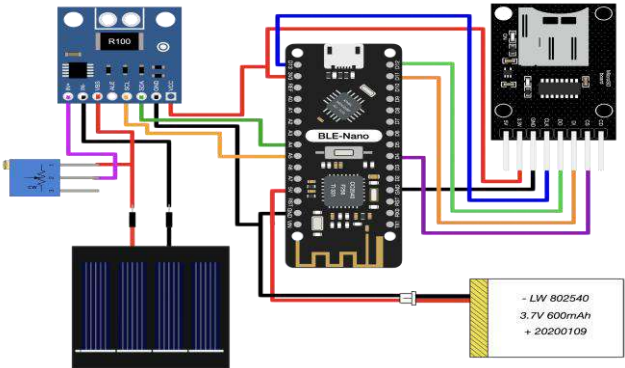


Fig 2.15: Hardware configuration for a wireless power monitoring node.

Finally, communication and real-time interfacing technologies play a crucial role in modern photovoltaic characterization systems. They enable accurate data transfer between sensors, microcontrollers, and computers while ensuring continuous monitoring of electrical parameters. Protocols such as I²C simplify sensor integration, whereas serial communication through USB/UART provides an efficient method for transmitting measured data in real time. Furthermore, visualization tools such as Microsoft Excel Data Streamer, MATLAB, and Python dashboards enhance data interpretation through live graphs and automated analysis. Therefore, the integration of these technologies significantly improves the efficiency, precision, and accessibility of low-cost PV monitoring and experimental systems.

Conclusion:

A thorough analysis of Photovoltaic (PV) characterization techniques, specifically focusing on the shift from manual to automated PV test methods, was presented within this Chapter. As well as demonstrating the need for reliable and consistent measurements for obtaining good quality I-V curves and evaluating PV module efficiency, it has been shown that the differences between commercial and Open-Source Data Acquisition System (DAQ) can be used to demonstrate how technology should be adapted to meet the needs of smaller laboratory and educational facilities found in many developing countries where high-cost testing equipment may not be available. In this regard, Arduino based DAQ's are emerging as a possible low-cost solution which meets the principles of Frugal Engineering.

In addition to examining the limitations of the traditional Rheostat Based Method of Electronic Load Control, it was concluded that this method is inefficient due to human error and cannot account for changing environmental conditions. Conversely, the MOSFET based electronic load has been proven to be a rapid, precise and programmable technique capable of accurately simulating different resistive loads by being operated in its linear mode.

Based on the above fundamental concepts, the next chapter will present the development of an inexpensive PV Analyzer using an Arduino Platform. This PV Analyzer will include electronic load control and real time data collection/communication capabilities to create a highly efficient, intelligent, and accessible tool for characterizing PV systems.

**Chapter 3: Design and Implementation of the
Arduino-Based**

I-Introduction:

This chapter presents the detailed design and implementation of the Arduino-based PV analyzer system, focusing on the 'how' behind the proposed solution. The objective is to transform the concept of a low-cost, open-hardware photovoltaic characterization tool into a functional hardware-software system. The architecture integrates an 80W PV module, a MOSFET-based electronic load, and a high-precision digital sensing system interfaced with an Arduino microcontroller, communicating with a PC for real-time monitoring and data logging. The chapter is structured to first describe the overall system architecture, followed by the selection and sizing of key hardware components, the design of the control circuitry, the development of the embedded software, and finally the implementation of safety protocols to ensure reliable and safe operation throughout the measurement process.

3.1 System Architecture:

The proposed low-cost photovoltaic (PV) analyzer consists of five major hardware elements: the PV module, an Arduino Mega 2560 as the central processing unit, a MOSFET-based electronic load, a digital sensing system (INA219), and a PC for data visualization (Figure 3-1).

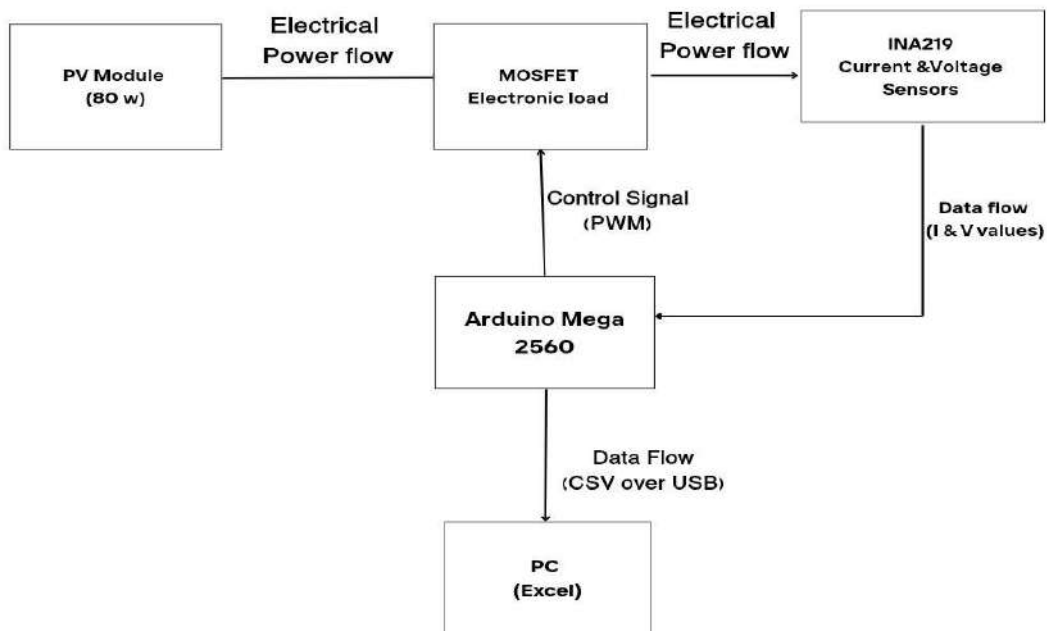


Figure 3-1: Block diagram of the proposed system architecture.

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The PV module serves as the primary power source. Its output is connected to a MOSFET, which functions as a variable electronic load. By operating the MOSFET in its linear region, the resistance is precisely controlled via the gate voltage, enabling an automated sweep to trace the complete I-V curve (Amiry et al., 2018).

The Arduino Mega 2560 acts as the system's brain, chosen for its expanded memory and peripheral capabilities. It generates a Pulse-Width Modulation (PWM) signal, which is filtered by an RC low-pass circuit to produce a smooth DC voltage for the MOSFET gate. For high-precision data acquisition, the system utilizes the INA219 digital sensor. Unlike traditional analog sensors, the INA219 integrates an internal ADC and communicates with the Mega via the I²C protocol (SDA/SCL). This digital approach minimizes noise and eliminates the need for external voltage dividers, as the sensor measures both bus voltage and current through its integrated shunt resistor (Texas Instruments, n.d.).

Finally, the acquired data is transmitted to the PC via USB in CSV format. This allows for real-time visualization of the I-V and P-V curves using Excel Data Streamer, providing an efficient platform for performance analysis (Machado et al., 2025).

3.2 Hardware Components Selection and Specifications:

This section details the selection of the primary hardware components used in the PV analyzer. Each component was chosen based on its electrical characteristics, compatibility with the Arduino Mega 2560 microcontroller, and its ability to handle the power requirements of an 80W PV module.

3.2.1 Microcontroller Unit (Arduino Mega 2560):

The Arduino Mega 2560 is the central control unit of the PV analyzer, responsible for generating control signals, acquiring data from sensors, and managing communication with the PC. Based on the ATmega2560 microcontroller, it was specifically selected for this project due to several technical advantages over smaller boards like the Arduino Uno.

First, the Arduino Mega provides a larger number of Pulse Width Modulation (PWM) channels. This is essential for the precise control of the MOSFET-based electronic load discussed in Section 3.3. Second, it features dedicated hardware I²C pins (SDA 20 and SCL 21), which ensure stable and high-speed communication with the INA219 power monitor. Furthermore, the board offers 256 KB of flash memory and 8 KB of SRAM, providing a

Chapter 3: Design and Implementation of the Arduino Based

significant overhead for complex data-logging algorithms and future software expansions, such as integrating an LCD or an SD card module for standalone operation (Arduino, 2018).

The board operates at a logic level of 5V, making it natively compatible with the IRLZ44N logic-level MOSFET without requiring additional level shifters. Its robust power management and USB-to-Serial communication interface facilitate real-time data transmission to Excel for I-V curve plotting

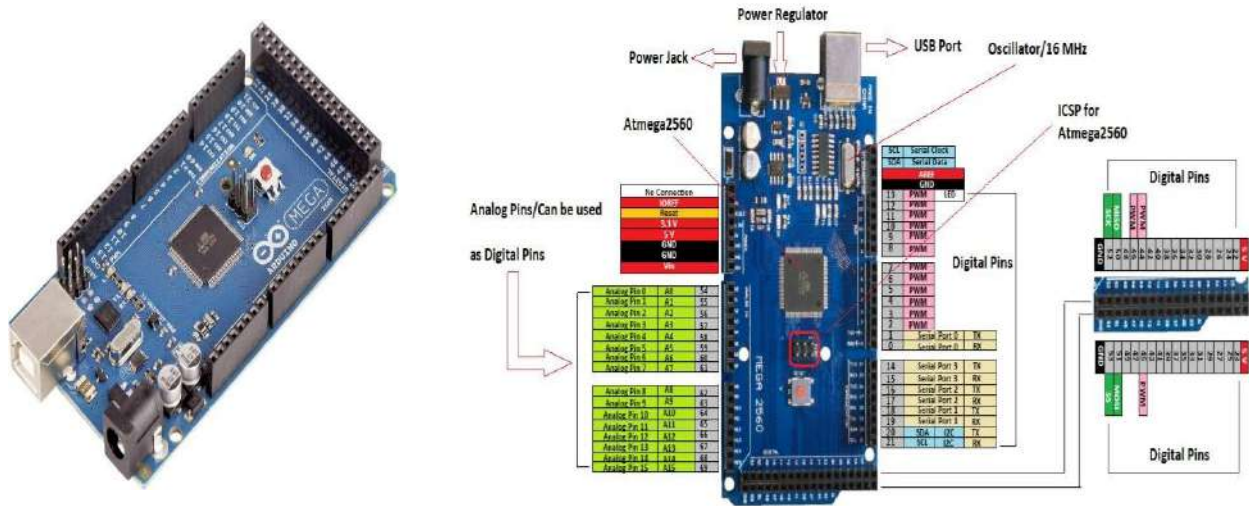


Figure 3-2: Arduino Mega 2560 Microcontroller

3.2.2. MOSFET Selection for 80W Power Handling:

The IRLZ44N logic-level N-channel power MOSFET was selected as the electronic load for this system. Unlike standard MOSFETs that require higher gate voltages, the IRLZ44N is a logic-level device, meaning it can be fully driven by a gate-source voltage V_{GS} of 5V. With a gate threshold voltage ($V_{GS(th)}$) between 1.0V and 2.0V, it is perfectly compatible with the Arduino Mega's 5V PWM output pins. This compatibility simplifies the design by eliminating the need for complex gate-driver circuitry (International Rectifier, n.d.).

Technically, the IRLZ44N features a planar cell structure that provides a robust Safe Operating Area (SOA), which is essential for stability when operating in the linear region to sweep the I-V curve. Its electrical ratings provide a significant safety margin: a drain-source breakdown voltage (V_{DSS}) of 55V (exceeding the module's 22V VOC) and a continuous drain current (I_D) of 47A at 25°C, which far exceeds the module's 5A short-circuit current (International Rectifier, n.d.).

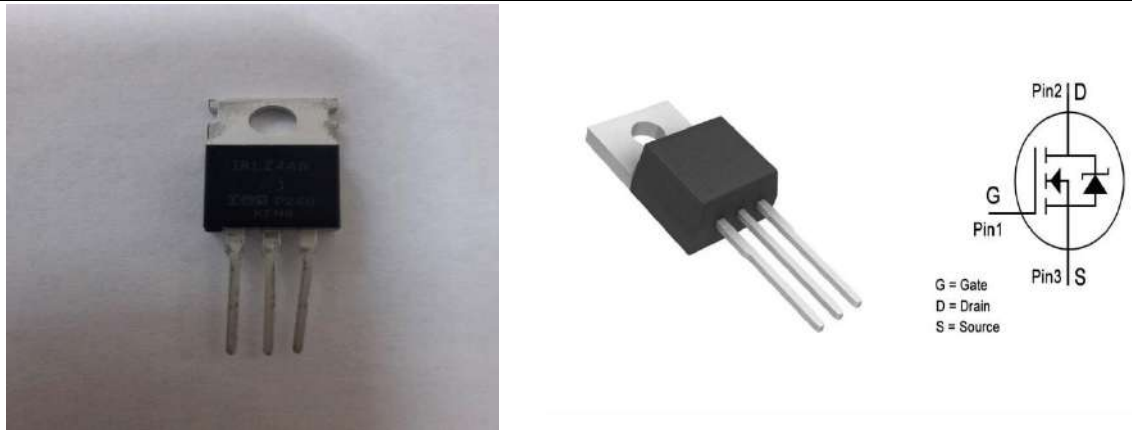


Figure 3-3: The IRLZ44N MOSFET.

3.2.3. Current and Voltage Sensor Integration (INA219):

For precise data acquisition, the INA219 digital power monitor from Texas Instruments was integrated into the system. This sensor communicates with the Arduino Mega via the I²C protocol (SDA and SCL lines), ensuring high immunity to electrical noise a critical factor for outdoor testing (Texas Instruments, n.d.).

The selected INA219 module incorporates a 0.1Ω (R100) precision shunt resistor for current measurement. By offloading the analog-to-digital conversion to the sensor's internal 12-bit ADC, the system achieves significantly higher resolution and noise immunity compared to the Arduino's built-in 10-bit ADC. The device can monitor bus voltages up to 26V and calculate current and power internally. This digital approach minimizes the component count by eliminating the need for external voltage dividers and operational amplifiers, while providing an ideal balance between measurement sensitivity and minimal power loss at the module's peak current (Texas Instruments, n.d.).

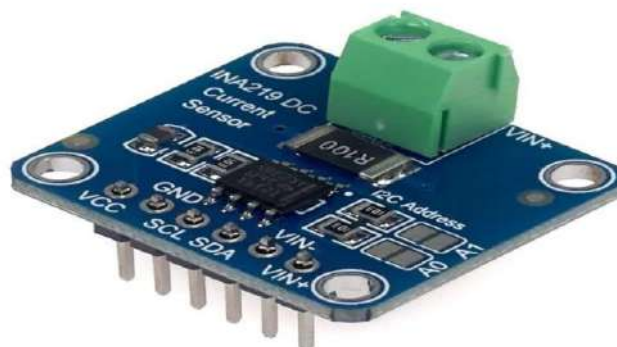


Figure 3-4: INA219 Sensor.

3.2.4. Thermal Management Design (Heatsink and Fan Calculations):

Operating the IRLZ44N MOSFET in its linear region generates heat because both a significant drain-source voltage (V_{DS}) and drain current (I_D) are present across the device simultaneously. The power dissipated in the MOSFET is calculated using the fundamental relationship: (International Rectifier, n.d.).

$$P_D = V_{(DS)} \times I_D$$

For an 80W PV module with open-circuit voltage $V_{OC} \approx 22V$ and short-circuit current $I_{SC} \approx 5A$, the power dissipation in the MOSFET does not reach the full 80W rating of the panel. Based on standard power electronics design principles, the actual peak power dissipation occurs near the midpoint of the I-V sweep and is practically estimated between 15W and 20W for this application.

•Importance of Heatsink:

According to the official IRLZ44N datasheet, the device has a maximum junction temperature ($T_{J,max}$) of 175°C and a junction-to-ambient thermal resistance (R_{thJA}) of 62°C/W when no heatsink is attached (International Rectifier, n.d.). Using this value, the junction temperature without any cooling can be calculated as:

$$T_J = T_A + (P_D \times R_{thJA}) \quad (3-1)$$

Assuming a worst-case ambient temperature (T_A) of 40°C (accounting for hot outdoor conditions) and a conservative power dissipation of 20W:

$$T_J = 40 + (20 \times 62) = 40 + 1240 = 1280^\circ C \quad (3-2)$$

This far exceeds the maximum rated junction temperature of 175°C, clearly demonstrating that a heatsink is absolutely necessary (International Rectifier, n.d.).

•Thermal Model and Governing Equations:

The standard thermal model for cooling a power MOSFET consists of three thermal resistances connected in series: junction-to-case (R_{thJC}), case-to-heatsink (R_{thCS}), and heatsink-to-ambient (R_{thSA}) (Texas Instruments, 2019). The thermal resistance network is illustrated in Figure 3-5:

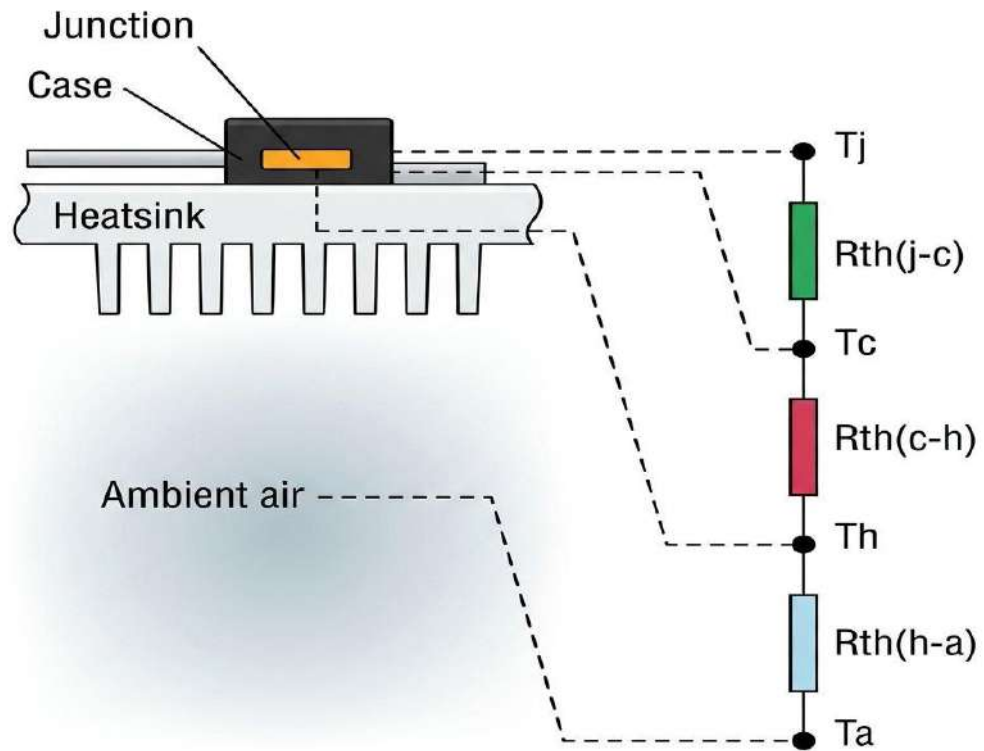


Figure 3-5: Equivalent thermal resistance network for the MOSFET cooling system
(Adapted from Melito et al., 2015).

The junction temperature is given by:

$$T_J = P_D \times (R_{thJC} + R_{thCS} + R_{thSA}) + T_A \quad (3-3)$$

Where:

- T_J : Junction temperature ($^{\circ}\text{C}$)
- P_D : Power dissipated in the device (W)
- R_{thJC} : Junction-to-case thermal resistance ($^{\circ}\text{C}/\text{W}$)
- R_{thCS} : Case-to-heatsink thermal resistance ($^{\circ}\text{C}/\text{W}$)
- R_{thSA} : Heatsink-to-ambient thermal resistance ($^{\circ}\text{C}/\text{W}$)
- T_A : Ambient temperature ($^{\circ}\text{C}$)

▪Calculating the Required Heatsink Thermal Resistance:

From the IRLZ44N datasheet, the junction-to-case thermal resistance is $R_{thJC} = 1.4^{\circ}\text{C/W}$ (International Rectifier, n.d.). The case-to-heatsink resistance is estimated at 0.5°C/W when thermal paste is applied. Using a worst-case power dissipation of $P_D = 20\text{W}$ and $T_A = 40^{\circ}\text{C}$, the total allowable thermal resistance is calculated as:

$$R_{th,total} = \frac{T_{J,max} - T_A}{P_D} = \frac{175 - 40}{20} = \frac{135}{20} = 6.75^{\circ}\text{C/W} \quad (3-4)$$

Therefore, the required heatsink-to-ambient thermal resistance is:

$$R_{thSA} = R_{th,total} - R_{thJC} - R_{thCS} = 6.75 - 1.4 - 0.5 = 4.85^{\circ}\text{C/W} \quad (3-5)$$

This calculation indicates that a heatsink with a thermal resistance of 4.85°C/W or lower is required to keep the IRLZ44N junction temperature within the safe limit of 175°C (International Rectifier, n.d.; Texas Instruments, 2019).

The aluminium heatsinks selected for this application (approximately $50\text{mm} \times 50\text{mm} \times 25\text{mm}$) is shown in Figure 3-6/3-7:

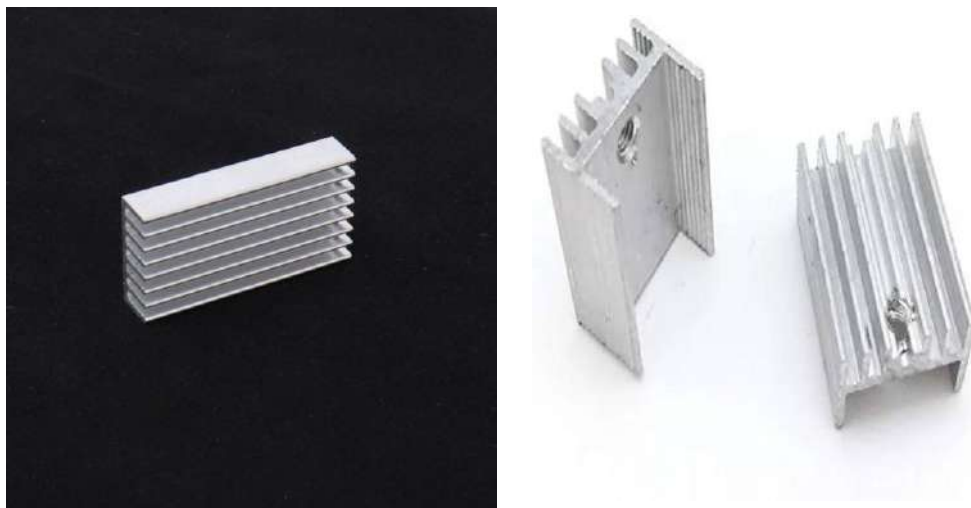


Figure 3-6: Different types of aluminium heatsinks evaluated for the project.

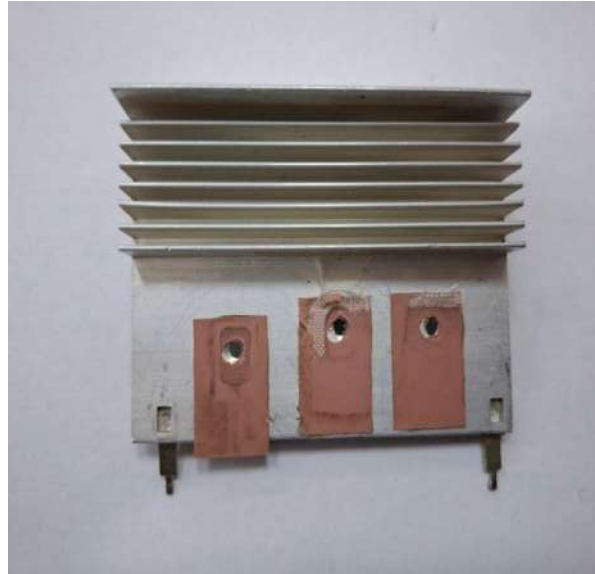


Figure 3-7: The heatsink we use in our project.

▪Air Fan Role:

Typical passive aluminium heatsinks of reasonable size (approximately 50mm × 50mm × 25mm) offer thermal resistances between 8°C/W and 15°C/W, which is significantly higher than the required 4.85°C/W. Therefore, a passive heatsink alone cannot achieve the required thermal performance (Microchip Technology, 2008).

To meet the calculated requirement, an active cooling system combining a high-surface-area aluminium heatsink with a 12V DC fan is implemented. The cooling fan is shown in Figure3-8:



Figure 3-8: 12V DC cooling fan for MOSFET active thermal management.

Forced-air cooling can reduce the effective thermal resistance by a factor of 2 to 3 compared to natural convection, allowing the system to achieve the required 4.85°C/W while maintaining reasonable heatsink size and cost (Microchip Technology, 2008).

This active cooling solution ensures that the IRLZ44N MOSFET remains within its safe operating area (SOA) during continuous I-V curve tracing cycles, preventing thermal runaway and ensuring long-term device reliability (International Rectifier, n.d.).

3.3 Control Circuitry: The RC Low-Pass Filter:

The Arduino Mega 2560 generates a Pulse-Width Modulation (**PWM**) signal on its digital pins to control the gate voltage of the **IRLZ44N** MOSFET. However, the PWM signal is a square wave that rapidly switches between 0V and 5V at a frequency of approximately **490 Hz** on most pins, or **980 Hz** on pins 5 and 6 (Arduino Stack Exchange, 2012; skillbank, n.d.). Applying this pulsating signal directly to the MOSFET gate would force it to switch rapidly between fully on and fully off states, creating unwanted switching noise and preventing stable operation in the linear region as a variable resistor (skillbank, n.d.).

Therefore, a method to convert the PWM signal into a smooth, continuous analog voltage is required. The most straightforward and cost-effective solution is a first-order Resistor-Capacitor (RC) low-pass filter (raw.org, 2026), as illustrated in Figure3-9:

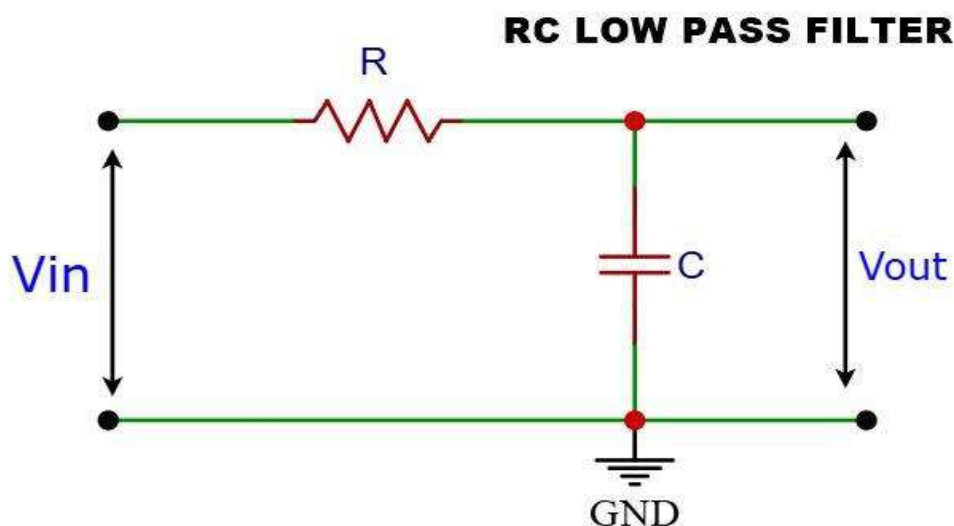


Figure 3-9: RC low- pass filter circuit.

This circuit consists of a single resistor (R) in series with the signal path and a capacitor (C) connected between the output and ground. When the PWM signal is **HIGH**, the capacitor charges through the resistor; when the signal is **LOW**, the capacitor discharges. If the charging/discharging time is long compared to the PWM period, the voltage across the

capacitor stabilizes, smoothing the rapid pulses into a steady DC level equal to the average voltage of the PWM signal (skillbank, n.d.; raw.org, 2026).

The behavior of the RC filter is characterized by its time constant (τ) and cut-off frequency (f_c). The time constant, which determines how quickly the capacitor charges (skillbank, n.d.), is given by:

$$\tau = R \times C \quad (3-6)$$

The cut-off frequency, where the filter begins to significantly attenuate the signal, is calculated as:

$$f_c = \frac{1}{2\pi \times R \times C} \quad (3-7)$$

(raw.org, 2026; skillbank, n.d.). For effective smoothing, the cut-off frequency should be significantly lower than the PWM frequency, typically by a factor of 10 to 50 (Arduino Forum, 2017).

For this project, using the Arduino's default 490 Hz PWM frequency, a target cut-off frequency of approximately 10 Hz is recommended (raw.org, 2026). Solving for practical component values, a common and effective combination is a 10 k Ω resistor and a 4.7 μ F capacitor. By substituting these selected values into the cut-off frequency formula, the result is:

$$f_c = \frac{1}{2 \times \pi \times 10,000 \times 4.7 \times 10^{-6}} \approx 3.38 \text{ Hz.} \quad (3-8)$$

This yields a cut-off frequency of approximately 3.4 Hz, which ensures excellent smoothing while maintaining a reasonable response time (Arduino Forum, 2017; raw.org, 2026). Alternatively, for even cleaner output, two cascaded RC stages each with R = 3.3 k Ω

and $C = 4.7 \mu\text{F}$ can be used, providing improved ripple suppression at the same PWM frequency (raw.org, 2026).

Despite its simplicity and low cost, the traditional RC low-pass filter approach presents significant limitations in high-precision PV characterization. Experimentally, the filter introduces a persistent voltage ripple on the MOSFET gate, which destabilizes the operating point during the I-V sweep. Furthermore, to minimize this ripple, a higher time constant ($\tau = R \times C$) is required, which consequently increases the settling time. This induces a substantial delay (up to 250 ms per measurement step), making the overall scanning process slow and susceptible to transient atmospheric changes. Finally, the system remains strictly constrained by the 8-bit resolution (256 steps) of the Arduino's hardware PWM, limiting the smoothness and density of the captured data points.

3.4 Hardware Optimization: Integration of the MCP4725 I²C DAC:

To overcome the structural limitations of the PWM-driven RC filter specifically the trade-off between voltage ripple and settling delays the system architecture was upgraded by integrating a dedicated digital-to-analog solution. Instead of smoothing a high-frequency digital square wave, an external MCP4725 12-bit Digital-to-Analog Converter (DAC) was introduced to achieve direct, pure, and high-resolution analog voltage control. This hardware enhancement completely eliminates the need for passive filtering, shifting the design from a traditional microcontroller approximation to an industrial-grade electronic load controller.

To enhance the precision of the gate voltage control for the IRLZ44N MOSFET, the MCP4725 12-bit DAC is integrated into the system. The MCP4725, manufactured by Microchip Technology, is a low-power, high-accuracy, single-channel buffered voltage output DAC with on-board non-volatile memory (EEPROM) (Microchip Technology, 2009).

Unlike the conventional PWM-to-analog approach using an RC filter which can introduce ripple and requires settling time the MCP4725 generates a true analog voltage directly from a digital value sent by the Arduino via the I²C protocol. This DAC operates from a single 2.7 v to 5.5 v supply and communicates over the I²C bus using the SDA and SCL lines, sharing the same two-wire interface already used by the INA219 sensor (Microchip Technology, 2009). According to the manufacturer's datasheet, the device offers a resolution of 12 bits (4096 steps), providing significantly finer voltage control than the 8-bit PWM (256 steps) available from the Arduino's analogWrite () function (Microchip Technology, 2009).

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The MCP4725 features a fast-settling time of 6 μ s (typical), rail-to-rail output swing, and very low differential non-linearity (DNL) of ± 0.2 LSB typical (Microchip Technology, 2009). The output voltage is proportional to the supply voltage, meaning that when powered from 5v, the DAC can output a clean analog voltage from 0v to 5v. The mathematical relationship is expressed as follows:

$$V_{OUT} = \frac{V_{DD} \times D_n}{4096} \quad (3-9)$$

Where D_n represents the 12-bit digital input code (0 to 4095) (Microchip Technology, 2009).

An important feature of the MCP4725 is its integrated EEPROM memory. The user can store a DAC input code in non-volatile memory, allowing the device to retain the last programmed output voltage even after power-off and to restore it automatically upon power-up (Microchip Technology, 2009). This is particularly useful in applications requiring a known initial gate voltage without re-initializing the DAC each time the system starts.

The MCP4725 requires only a few connections: V_{DD} to the Arduino's 5v supply, GND to common ground, SDA to the Arduino's I^2C data line (pin 20 on the Mega 2560), SCL to the I^2C clock line (pin 21 on the Mega 2560), and V_{OUT} connected directly to the gate of the IRLZ44N MOSFET (optionally through a small resistor for protection). The default I^2C address of the MCP4725 is 0x60 (or 0x62 depending on breakout board configuration), but it can be adjusted by pulling the A0 pin HIGH or LOW, allowing multiple DAC devices on the same communication bus (Adafruit Industries, n.d.). Adafruit provides a convenient Arduino library (Adafruit_MCP4725) that simplifies controlling the DAC, allowing the user to set the output voltage directly within the firmware (Adafruit Industries, n.d.).

Compared to the RC filter method, the MCP4725 offers several advantages: it produces a perfectly clean DC voltage without any ripple, it does not require waiting for RC settling (eliminating the 250ms delay per step), it provides higher resolution (12-bit vs. 8-bit effective), and it simplifies the circuit by replacing two passive components (R and C) with a single integrated circuit. However, it does require an additional I^2C device on the bus and a small additional cost (approximately \$2-3). For applications demanding superior analog control precision and faster sweeping, the MCP4725 is a worthwhile enhancement to the basic RC filter design.

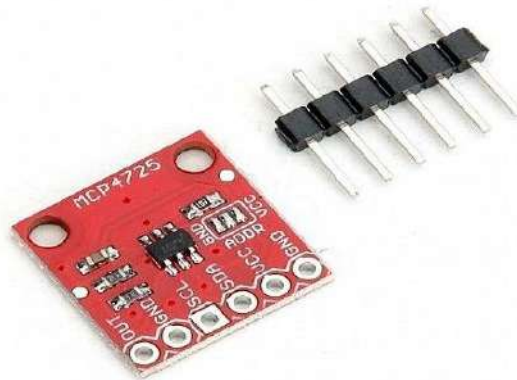


Figure 3.10: The MCP4725 I²C DAC

3.5 Software Development:

3.5.1 The Arduino "Sweep" Algorithm Logic:

To trace the I-V curve of the PV module, the Arduino Mega 2560 must automatically vary the load resistance across the entire operating range. This is achieved by implementing a sweep algorithm that systematically changes the duty cycle of the PWM signal sent to the gate of the IRLZ44N MOSFET. The algorithm uses a simple for loop to increment the PWM value from 0 to 255, which corresponds to increasing the duty cycle from 0% to 100% (Circuit Digest, 2021). As the duty cycle increases, the filtered analog voltage at the MOSFET gate rises from 0V to 5V, progressively reducing the load resistance seen by the PV module (RST Wiki, 2024).

For each distinct PWM step, the algorithm pauses for a stabilization delay of approximately 250 milliseconds. This delay is critical because it allows the RC filter circuit (with a time constant of 47ms) to settle to approximately 99% of its final value before measurements are taken. Based on the RC filter design in Section 3.3, where $\tau = R \times C = 47\text{ms}$, five-time constants ($5\tau \approx 235\text{ms}$) are required for full settling. This delay ensures that the MOSFET reaches a stable operating point before measurements are taken (Circuit Digest, 2021). After the delay, the Arduino communicates with the INA219 sensor via the I²C bus to read the instantaneous current (I) and voltage (V) values. The library functions provided by Adafruit simplify this process, allowing the Arduino to request the bus voltage, shunt voltage, and calculated current directly (Adafruit, 2019). Each pair of voltage and current values forms a single data point on the I-V curve.

The sweep is typically performed from open-circuit (0% duty cycle) to short-circuit (100% duty cycle). The number of sweep steps can be adjusted in the code from 50 to 200 points, depending on the desired balance between resolution and measurement speed. A typical configuration of 100 steps yields a total sweep time of approximately 25 seconds, offering a practical trade-off for laboratory characterization of 80W PV modules under stable environmental conditions (curiouselectric, 2020; Circuit Digest, 2021).

3.5.2 Data Formatting for Real-Time Excel Streaming:

After the Arduino acquires each voltage and current measurement point, the data must be transmitted to a PC for visualization, analysis, and storage. The standard method for real-time data streaming from an Arduino to a host computer is to format the data as Comma-Separated Values (CSV) and send it over the USB serial connection (Microsoft Learn, 2025).

In the CSV format, each data point is transmitted as a single line of text containing the voltage and current values separated by a comma. For example, a typical measurement point would be sent as: "**18.45,2.34**" (Microsoft Learn, 2025). The line is terminated by a newline character (`\n`), which data logging software recognizes as the end of a single record (RST Wiki, 2024).

The Arduino code implements this using the standard Serial library. The voltage value is sent with `Serial.print(voltage)`, followed by a comma with `Serial.print(",")`, and finally the current value with `Serial.println(current)`, which automatically appends the newline character (Circuit Digest, 2021). The serial port is initialized in the `setup ()` function with `Serial.begin(9600)` to set the communication baud rate to 9600 bits per second, which is compatible with most data logging applications (Adafruit, 2019).

On the receiving side, this project leverages Microsoft Excel Data Streamer, a free add-in designed specifically for real-time data capture from serial-enabled devices such as the Arduino UNO or Mega (Microsoft Learn, 2025). After connecting the Arduino via USB, the user opens the Data Streamer add-in in Excel, selects the correct COM port, and clicks "Start Data." The software automatically parses the incoming CSV stream and populates the Data In worksheet with the values in real time (Microsoft Learn, 2025).

As the Arduino's for loop progresses through each PWM step, each new line of CSV data creates a new row in the Excel worksheet, allowing the user to instantly observe the I-V curve being constructed point by point (curiouselectric, 2020). From this live data, Excel can generate real-time scatter plots to visualize the I-V and P-V curves as the measurement is

Chapter 3: Design and Implementation of the Arduino Based

conducted. As previously detailed in Section 3.4, the MCP4725 I²C DAC serves as the gate voltage controller in this system, replacing the conventional PWM-RC filter approach to ensure a clean and ripple-free analog output. The complete interaction between all software tools, the Arduino hardware, and the PV system components is illustrated in Figure 3-11:

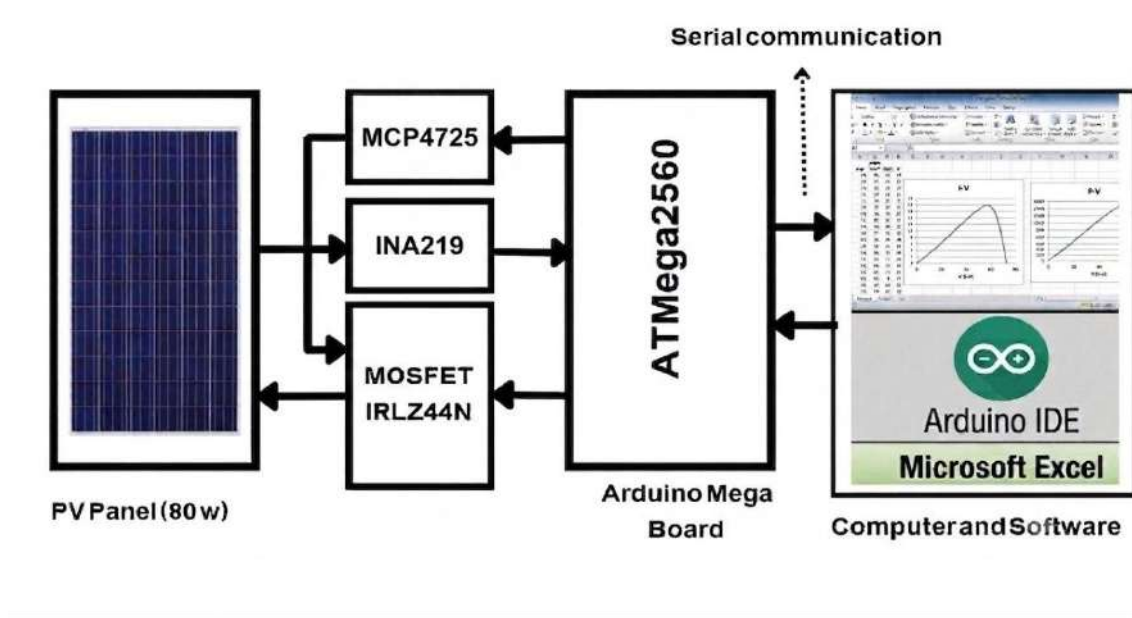


Fig. 3-11: System block diagram illustrating hardware-software integration and serial data flow.

This capability provides immediate feedback on system operation, enables rapid verification of measurement quality, and allows for on-the-fly adjustments to the testing parameters (curiouselectric, 2020; RST Wiki, 2024).

3.6 Safety Protocols (Overcurrent and Overtemperature Protection):

To ensure the longevity and safe operation of the PV analyzer, a multi-layered protection strategy is implemented, combining software-based monitoring with a hardware fail-safe. This dual-layer approach is standard practice in power electronics design and significantly enhances the system's reliability by providing redundancy (Texas Instruments, 2016). The system is designed to protect the IRLZ44N MOSFET, which has a maximum junction temperature of 175°C and a continuous drain current of 47A, as specified by its datasheet (International Rectifier, n.d.).

3.6.1 Overcurrent Protection (OCP):

The Arduino continuously monitors the current flowing from the PV module. It reads the INA219 sensor at regular intervals, which communicates via the I²C bus and provides high-resolution current data with a 12-bit ADC built into the sensor (Texas Instruments, 2011). A safety threshold of 5.5A is set in the code, conservatively chosen to be slightly above the 80W modules short-circuit current ($\approx 5A$) but well below the IRLZ44N's maximum rating of 47A (International Rectifier, n.d.). If the measured current exceeds this 5.5A limit, the protection logic is triggered instantly. The Arduino program executes a shutdown routine by setting the PWM output to zero (analog Write (pwmPin, 0)). This action turns off the IRLZ44N MOSFET, effectively disconnecting the electronic load from the PV module and preventing any further current flow (elshazlio, 2024).

3.6.2 Overtemperature Protection (OTP):

For temperature monitoring, an LM35 precision temperature sensor is attached to the MOSFET's heatsink with thermal paste. According to the LM35 datasheet, this sensor produces an output voltage linearly proportional to the temperature in Celsius, with a scale factor of 10mV per degree Celsius (Texas Instruments, 2016). This eliminates the need for complex logarithmic conversion equations, simplifying both the code and calibration process. The Arduino reads this analog voltage and calculates the heatsink temperature. A conservative protection threshold of 80°C is established. If the measured temperature exceeds 80°C, the OTP routine triggers a system shutdown, setting the PWM output to zero. This prevents thermal runaway, a dangerous condition where the MOSFET's rising temperature

increases its conductivity, leading to even more current and heat in a self-sustaining cycle until the device fails catastrophically (Engineer Live, 2018).



Figure 3-12: LM35 temperature sensor for overtemperature protection.

3.6.3 Hardware Fail-Safe (Secondary Layer):

As a final safety net in case the primary software layer fails, a 6.3A fast-blow fuse is connected in series with the PV module's positive output. This fuse is rated just above the module's nominal current but below the maximum ratings of the MOSFET. In the event of a catastrophic short circuit or a software failure where the code stops executing, this hardware layer will blow, permanently disconnecting the circuit and preventing fire or component damage (mustafaergul0, 2024).



Figure 3-13: 6,3 A fast-acting fuse used as a hardware fail-safe in the PV analyzer.

Conclusion:

In conclusion, this chapter has detailed the complete design and implementation of the Arduino-based PV analyzer, from the high-level system architecture to the underlying hardware and software components. The selected MOSFET and the high-precision digital sensing system, together with the thermal management strategy, enable accurate and safe handling of the 80W PV module under various load conditions. The control circuitry, based on an RC low-pass filter, ensures a stable gate drive for the MOSFET, while the Arduino software executes a sweep algorithm and formats the acquired data for real-time streaming to Excel. Finally, the implemented safety protocols, including overcurrent protection and thermal shutdown logic, provide robust safeguarding of the device and the user. With this foundation, the system is now ready for experimental validation and performance evaluation in the next chapter.

**Chapter 4: Experimental Results, Analysis,
and Discussion**

1.INTROUDCTION:

The preceding chapters established the theoretical foundations and described the hardware and software design of the proposed low-cost Arduino-based PV analyzer. This chapter shifts the focus toward experimental validation, where the developed system is tested under real outdoor conditions to assess its practical performance and measurement accuracy.

The experimental work was carried out in three progressive stages, beginning with a small solar cell, followed by a 3.5W solar cell, and concluding with an 80W monocrystalline solar panel. This incremental approach was adopted to verify the system's ability to operate correctly across a wide range of power levels. For each source, the system automatically generated both I-V and P-V characteristic curves, from which key electrical parameters such as open-circuit voltage, short-circuit current, maximum power point, and fill factor were extracted and analyzed.

Furthermore, a comparative evaluation was conducted between the automated Arduino-based measurements and the conventional manual method using a rheostat and a digital multimeter, in order to quantify the improvement in speed, resolution, and repeatability offered by the proposed system. The results presented in this chapter demonstrate that the developed analyzer successfully fulfills its design objectives as a reliable, accurate, and accessible alternative to traditional PV characterization tools.

4.1 Experimental Setup:

The experiments were conducted outdoors under natural sunlight conditions to ensure that the measurements accurately reflect the real-world performance of photovoltaic modules. Three different PV sources were tested sequentially: a small solar cell, a 3.5W solar cell, and a monocrystalline 80W solar panel ($rated V_{OC} \approx 22V$, $I_{SC} \approx 5A$), allowing the system to be validated across a wide range of power levels. All modules were oriented facing south at a tilt angle of approximately 30° to maximize solar irradiance absorption. Data collection was carried out on a clear sunny day in May 2026, between 11:00 AM and 2:00 PM, to ensure relatively stable and consistent illumination conditions throughout the testing period. Ambient temperature ranged between $32^\circ C$ and $38^\circ C$, while solar irradiance was estimated between 780 and 920 W/m^2 .

The measurement system was built around an Arduino Mega 2560 microcontroller, interfaced with an INA219 high-side current/voltage sensor, an MCP4725 12-bit digital-to-analog

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converter (DAC), an IRLZ44N logic-level MOSFET acting as the controllable electronic load, and an LM35 temperature sensor for real-time thermal monitoring. The DAC output was swept from 0 to 4095 in increments of 2, generating 2048 discrete load steps across the full operating range of each module. A stabilization delay of 40 ms was applied between each step to allow the transient electrical effects to settle before sampling. At each step, bus voltage, current, power, and temperature were recorded and transmitted via serial communication at a baud rate of 115200 to a PC for post-processing and curve generation in Excel.

Two software protection mechanisms were implemented to ensure component safety during operation. Current limiting was enforced by halting the sweep and resetting the DAC to zero whenever the measured current exceeded 3200 mA. Thermal protection was similarly triggered when the LM35 reading surpassed 60°C, at which point the sweep was immediately interrupted, the DAC was reset, following each complete sweep, a 10-second cooling delay was introduced before the next measurement cycle could begin to prevent heat accumulation in the electronic load.

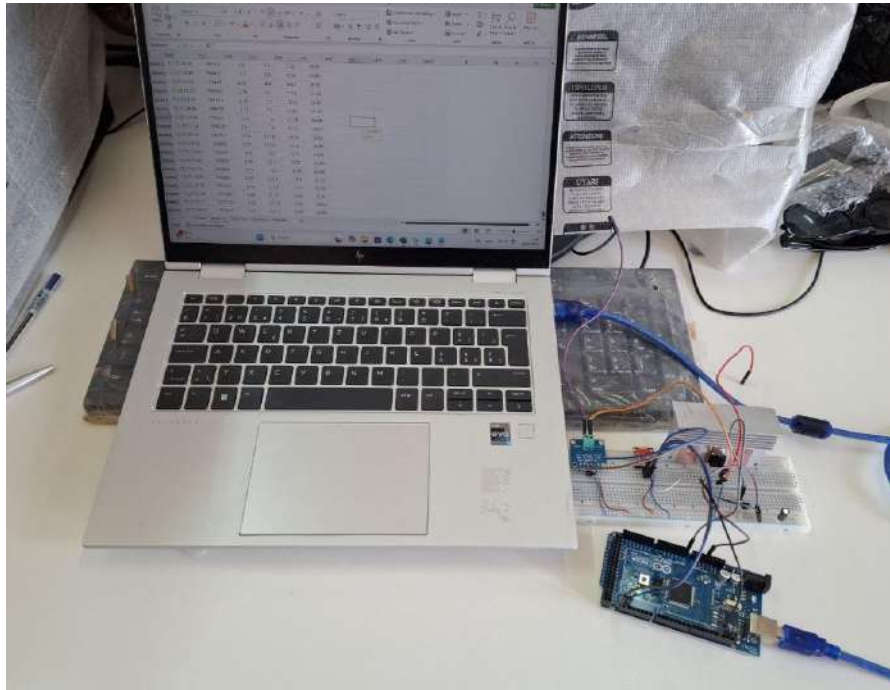


Figure 4.1: Experimental setup and hardware prototype of the developed Arduino-based PV analyzer during outdoor validation.

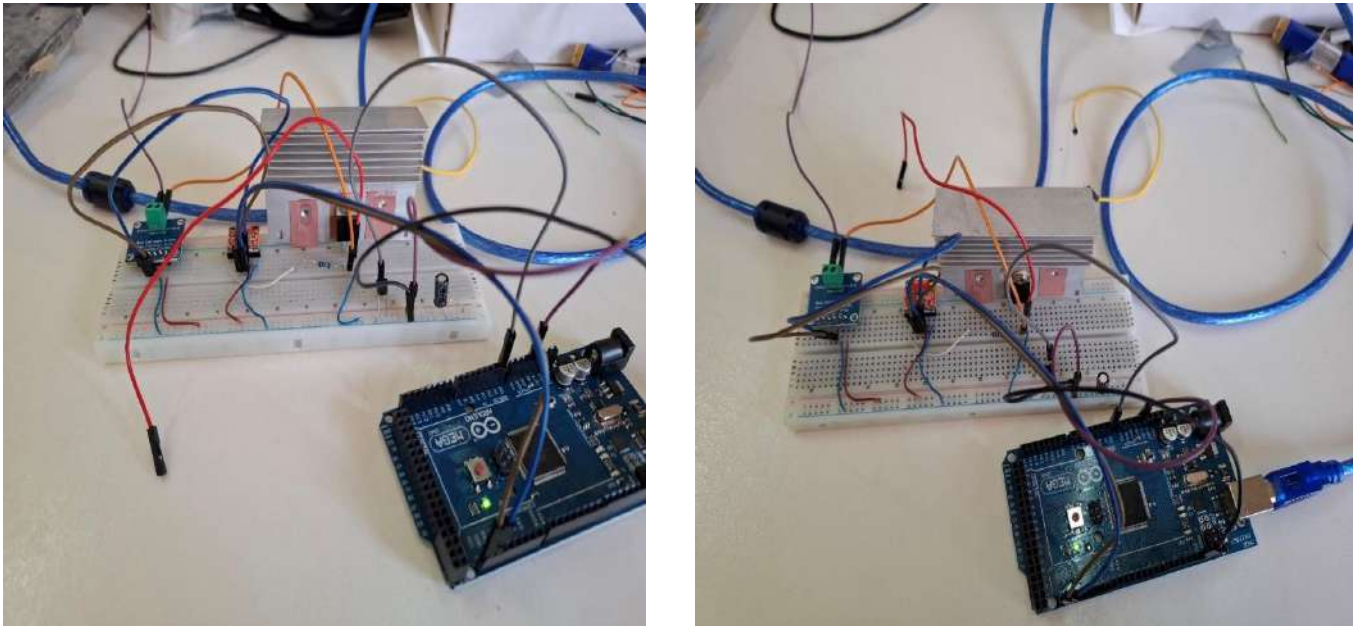


Figure 4.2: Hardware implementation and packaging of the characterization system prototype.

The experimental validation was systematically carried out across three distinct PV sources of increasing power levels, namely a small test cell, a 3.5W solar module, and an 80W monocrystalline solar panel, as shown in Figure 4.3, Fig 4.4 and Fig 4.5. This progressive approach ensured a comprehensive performance evaluation of the analyzer across a wide range of operating conditions.

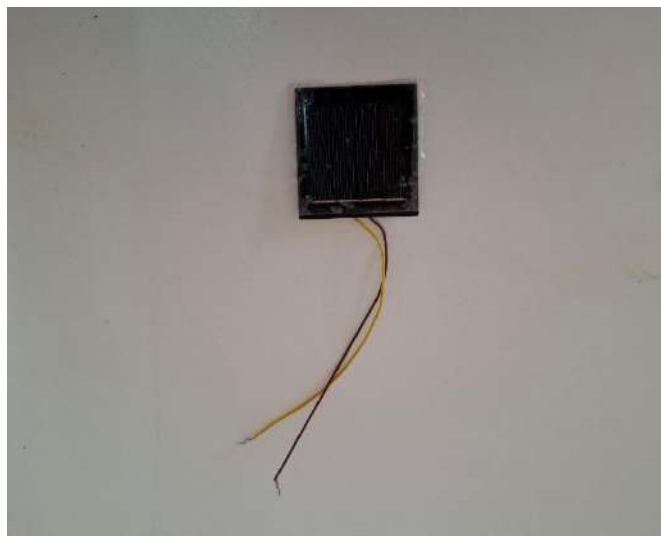


Fig 4.3: The small Cell.

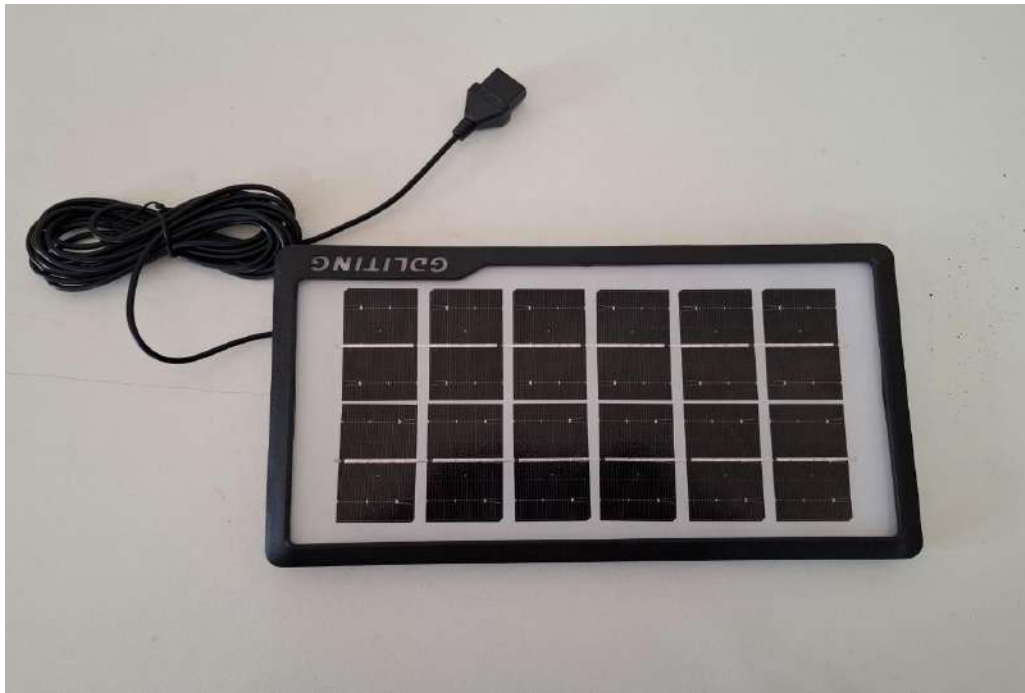


Fig 4.4: The 3,5 W Solar Module.



Fig 4.5: The 80 W PV panel.

4.2 Data Visualization:

The primary objective of this section is to present and interpret the characteristic curves generated by the developed PV analyzer for each tested source. The system successfully produced both I-V and P-V curves for three different photovoltaic sources of increasing power levels: a small solar cell, a 3.5W solar cell, and an 80W monocrystalline solar panel. All curves were generated automatically through a full DAC voltage sweep, and the resulting data was exported via serial communication and plotted in Microsoft Excel. The extracted key parameters for each source are discussed individually in the following subsections.

4.2.1 Small Solar Cell:

The I-V and P-V characteristic curves obtained for the small solar cell are presented in Figure 4.6 and Figure 4.7 respectively. The extracted electrical parameters are summarized in Table 4.1.

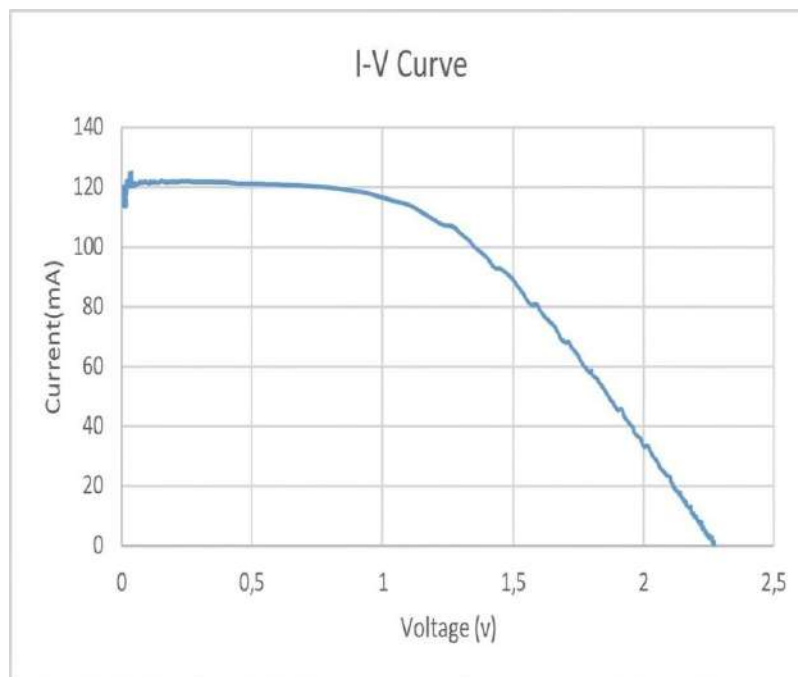


Fig 4.6: I-V Curve of the Small Test Cell

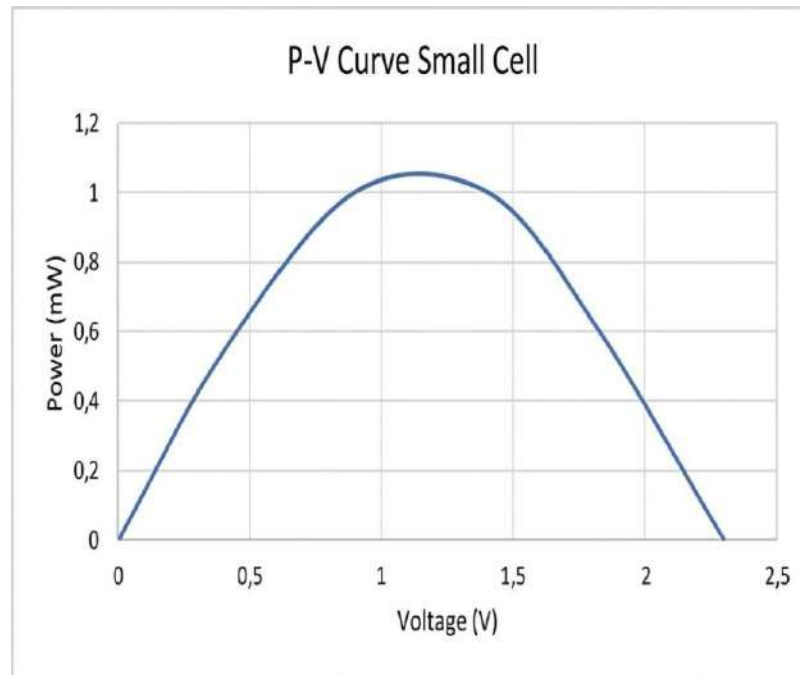


fig 4.7: P-V Curve of the Small Test Cell.

Based on the generated I-V and P-V curves, the key electrical parameters of the small solar cell were extracted and are summarized in Table 4.1 below:

Parameter	Value
Open-Circuit Voltage (Voc)	2,35 V
Short-Circuit Current (Isc)	121mA
Voltage at MPP (Vmpp)	1.1V
Current at MPP (Impp)	105mA
Maximum Power (Pmax)	1.05 mW
Fill Factor (FF)	0,369

Table 4.1: Extracted parameters for the small solar cell.

The I-V curve exhibits the expected classical behavior of a photovoltaic source, with a nearly constant short-circuit current of 121 mA sustained from zero voltage up to approximately 1.2 V, followed by a gradual decline until reaching $V_{oc} \approx 2.35$ V. Minor current fluctuations visible near the short-circuit region are attributed to measurement noise at low-impedance conditions, which is a common characteristic of low-cost analog sensing circuits and does not reflect a system fault. The P-V curve displays a well-defined maximum power point at $V_{mpp} \approx 1.1$ V, with a peak output power of $P_{max} \approx 1.05$ mW. The curve rises smoothly, reaches its peak symmetrically, and descends toward the open-circuit voltage, confirming the correct operation of the DAC sweep and the reliability of the INA219 power measurements. The computed Fill Factor of $FF \approx 0.369$ is relatively low, which is consistent with the expected behavior of small-area cells that typically exhibit higher internal series resistance relative to their active area. Notably, the successful characterization of a sub-milliwatt source confirms the sensitivity and wide dynamic range of the proposed system.

4.2.2 (3.5 W) Solar Module:

The I-V and P-V characteristic curves obtained for the 3.5W solar Module are presented in Figure 4.8 and Figure 4.9 respectively. The key electrical parameters extracted from both curves are summarized in Table 4.2 below:

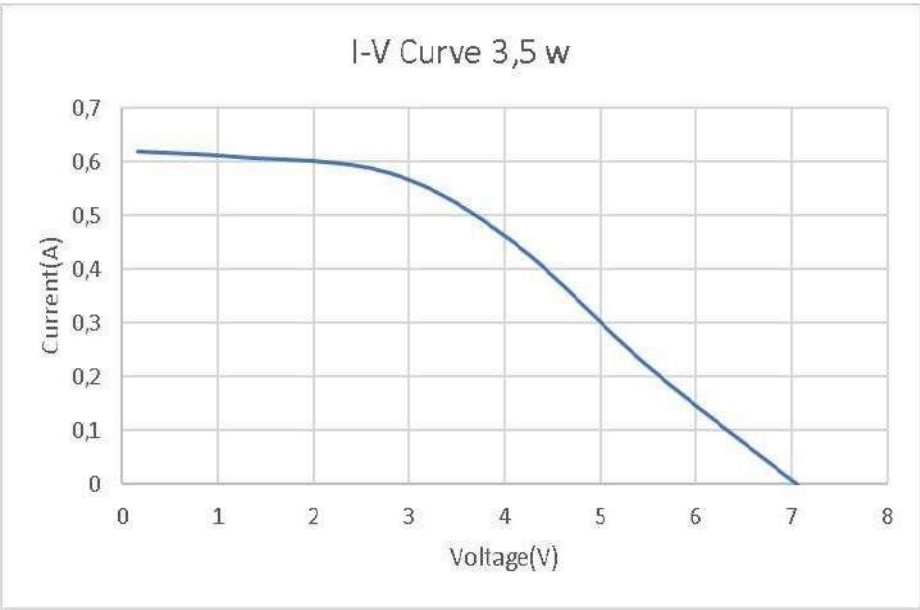


Fig 4.8: The I-V Curve of 3,5 W Solar Module.

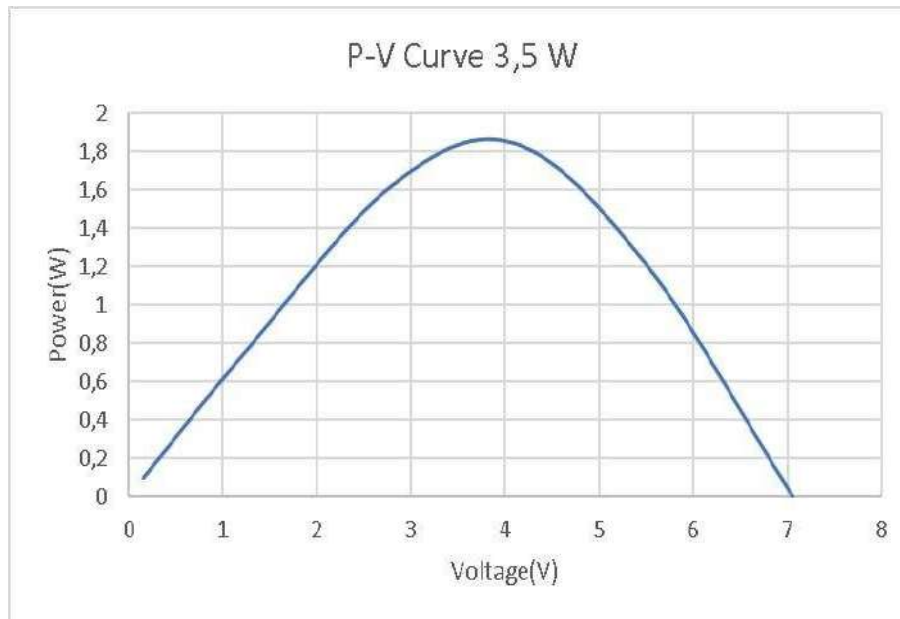


Fig 4.9: P-V Curve of 3,5 W Solar Module.

From the characteristic curves illustrated above, the key performance parameters were identified and are consolidated in Table 4.2 for clarity.

Parameter	Value
Open-Circuit Voltage (Voc)	7,1 V
Short-Circuit Current (Isc)	0,62 A
Voltage at MPP (V _{mpp})	3,8 V
Current at MPP (I _{mpp})	0,48 A
Maximum Power (P _{max})	1,85 W
Fill Factor (FF)	0,421

Table 4.2: Extracted parameters for the 3,5 W Solar Module.

The I-V curve demonstrates a well-defined classical photovoltaic characteristic, with a stable short-circuit current of approximately 0.62 A maintained from zero voltage up to roughly

2 V, followed by a smooth and gradual decline until reaching an open-circuit voltage of $V_{oc} \approx 7.1$ V. Compared to the small cell, this curve exhibits significantly less noise and improved smoothness, which is attributed to the higher current and voltage levels that fall more comfortably within the optimal sensing range of the INA219 sensor.

The P-V curve displays a clearly defined maximum power point at $V_{mpp} \approx 3.8$ V, corresponding to a peak output power of $P_{max} \approx 1.85$ W. The symmetric bell-shaped profile of the curve confirms the accurate operation of the DAC voltage sweep across the full operating range of the module. It is worth noting that the measured maximum power of 1.85 W is lower than the rated value of 3.5 W, which is expected since manufacturer ratings are specified under Standard Test Conditions (STC: 1000 W/m², 25°C), whereas the actual test conditions involved higher ambient temperatures and varying irradiance levels. The Fill Factor of $FF \approx 0.421$ is higher than that of the small cell, consistent with the general trend that larger PV modules tend to exhibit lower relative internal resistance and thus better curve squareness.

4.2.3 80W Solar Panel:

The I-V and P-V characteristic curves obtained for the 80W monocrystalline solar panel are presented in Figure 4.10 and Figure 4.11 respectively. The key electrical parameters extracted from both curves are summarized in Table 4.3 below.

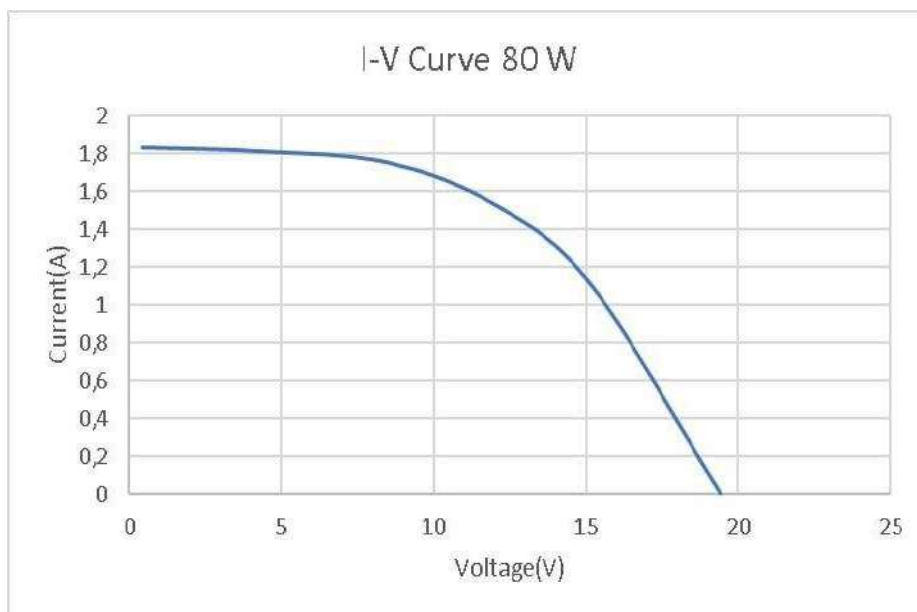


Fig 4.10: The I-V Curve of 80 W PV panel.

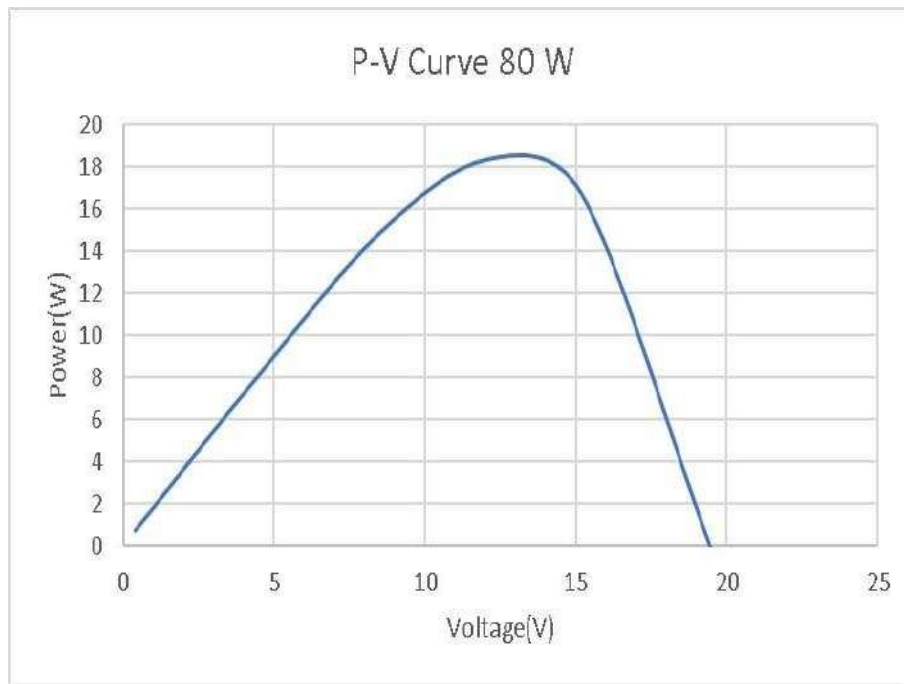


Fig 4.11: The P-V Curve of 80 w PV panel.

From the characteristic curves illustrated above, the key performance parameters were identified and are consolidated in Table 4.3 for clarity.

Parameter	Value
Open-Circuit Voltage (Voc)	19,5 V
Short-Circuit Current (Isc)	1,83 A
Voltage at MPP (Vmpp)	13,5 V
Current at MPP (Impp)	1,35 A
Maximum Power (Pmax)	18,2 W
Fill Factor (FF)	0,510

Table 4.3: Extracted parameters for the 80 w PV panel.

The I-V curve of the 80W panel represents the most well-defined and noise-free characteristic obtained among all three tested sources. A stable short-circuit current of approximately 1.83 A is maintained from zero voltage up to roughly 10 V, followed by a smooth and gradual decline until reaching an open-circuit voltage of $V_{oc} \approx 19.5$ V. The near-absence of measurement noise in this curve reflects the fact that the voltage and current levels of the 80W panel fall well within the optimal sensing range of the INA219 sensor, resulting in superior measurement quality compared to lower-power sources.

The P-V curve displays a sharply defined maximum power point at $V_{mpp} \approx 13.5$ V, corresponding to a peak output power of $P_{max} \approx 18.2$ W. The well-shaped bell profile of the curve further confirms the reliable operation of the full DAC sweep and the accuracy of the real-time power calculations. It should be noted that the measured peak power of 18.2 W is significantly lower than the rated value of 80 W, which is entirely consistent with the prevailing test conditions. The ambient temperature of 32–38°C and the measured irradiance of 780–920 W/m² both deviate considerably from the Standard Test Conditions (STC: 25°C, 1000 W/m²), naturally resulting in reduced output power. This behavior, rather than indicating a measurement error, actually demonstrates that the analyzer is correctly capturing the real-world operating performance of the panel. The computed Fill Factor of $FF \approx 0.510$ is the highest among the three tested sources, which is consistent with the superior build quality and lower relative internal resistance characteristic of industrial-grade monocrystalline panels.

4.3 Comparative Analysis:

In order to validate the performance of the developed Arduino-based PV analyzer, a reference measurement was conducted on the same 80W monocrystalline solar panel using the conventional manual method, consisting of a variable rheostat as a load and a digital multimeter to record the corresponding voltage and current values at each manually adjusted step. The resulting I-V and P-V curves obtained by both methods are presented in Figure 4.12 and Figure 4.8, and the extracted parameters are compared in Table 4.4.

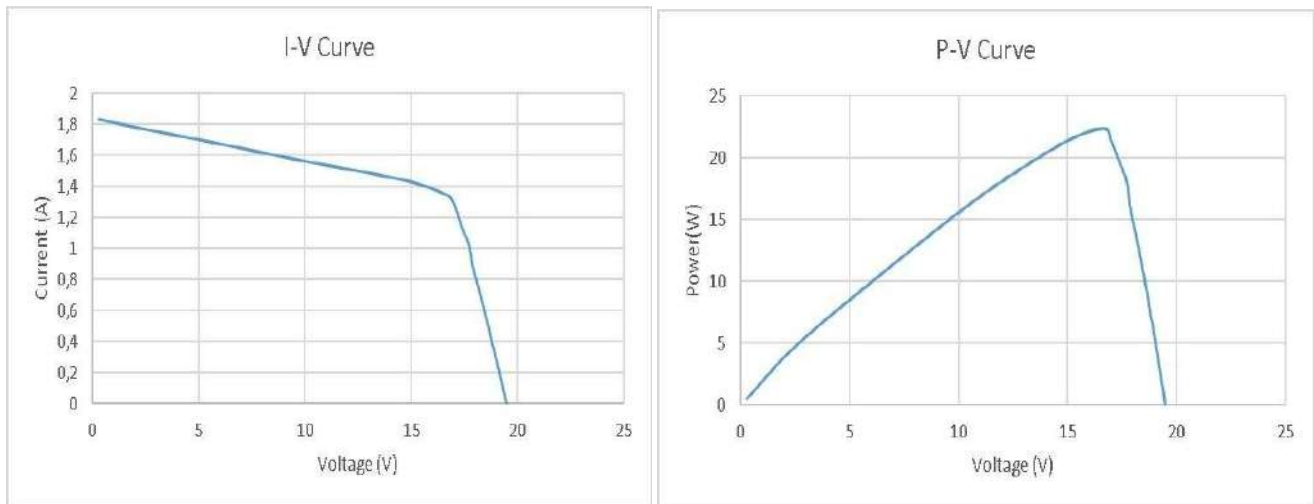


Fig 4.12: I-V and P-V Curves of 80 w Solar panel obtained using the conventional manual method (rheostat and digital multimeter).

Parameter	Arduino-Based System	Manual Method (Rheostat + Multimeters)	Difference
Voc	19,5 A	19,5 V	0,0 V
Isc	1,83A	1,83 A	0,0 A
Vmpp	13,5 V	16,5 V	3,0 V
Impp	1,35 A	1,35 A	0,0 A
Pmax	18,2 W	22,3 W	4,1 W
FF	0,510	0,624	0,114
Number of Points	2048	19	/
Measurement Time	25 s – 1 min	30 minutes	/

Table 4.4: Comparative summary between the Arduino-based analyzer and the manual rheostat method for the 80w solar panel.

The comparison reveals several significant observations. First, both methods produced identical values for V_{oc} and I_{sc} , the two boundary parameters of the I-V curve. This fundamental agreement confirms that the Arduino-based system delivers correct and trustworthy measurements that are fully consistent with those obtained through the established conventional approach.

Regarding curve quality, a clear visual difference is apparent between the two sets of curves. The Arduino-generated I-V curve, shown in Figure 4.12, displays a smooth and continuous profile built from 2048 uniformly distributed data points, allowing precise identification of all characteristic regions including the current-source region, the knee region, and the open-circuit point. In contrast, the manually obtained I-V curve, shown in Figure 4.12, exhibits a noticeably irregular and coarser profile due to the limited number of only 19 measurement points, which are insufficient to accurately capture the shape of the curve, particularly in the critical knee region where the maximum power point is located.

Concerning the P_{max} discrepancy, the manual method recorded a peak power of 22.3 W compared to 18.2 W measured by the automated system. This difference is not indicative of an error in the Arduino system, but rather reflects a fundamental limitation of the manual approach. Since the rheostat-based measurement required approximately 30 minutes to complete, the solar irradiance and atmospheric conditions varied considerably throughout the process, introducing inconsistency between data points recorded at different moments in time. The Arduino-based system, by contrast, completed the full voltage sweep in approximately 25 seconds, capturing the panel characteristics under a single, stable, and representative set of operating conditions. This makes the automated measurement inherently more consistent and physically meaningful.

The difference observed in the Fill Factor values (0.510 for Arduino vs 0.624 for the manual method) further illustrates the consequence of insufficient data resolution. With only 19 points, the manual method fails to accurately trace the transition region of the I-V curve, leading to an overestimation of the curve squareness and consequently an inflated Fill Factor value.

Overall, the comparative analysis demonstrates that the proposed Arduino-based PV analyzer successfully replicates the fundamental electrical characteristics obtained by the conventional method, while offering substantial improvements in measurement speed, data

resolution, curve smoothness, and temporal consistency, making it a more reliable and practical tool for real-world PV characterization.

4.4 Performance Evaluation:

This section provides a focused evaluation of the developed Arduino-based PV analyzer in terms of two key performance criteria: measurement speed and data resolution, both of which directly determine the practical usefulness of a PV characterization system.

In terms of measurement speed, the automated system demonstrated a clear and substantial advantage over the conventional approach. The complete I-V and P-V sweep was accomplished in a time ranging between 25 seconds and one minute, whereas the manual rheostat-based method required more than 30 minutes to record a limited set of data points collected at intervals of approximately half an hour between each reading. This considerable time difference makes the developed system far more suitable for real-world field applications, where solar conditions are continuously changing and prolonged measurement sessions introduce significant inconsistency between recorded data points.

In terms of measurement resolution, the automated system recorded more than 2000 data points uniformly distributed across the full voltage sweep range during each measurement cycle, compared to the sparse and manually collected readings of the conventional method taken at fixed time intervals. This dramatic difference in data density is directly reflected in the quality of the resulting characteristic curves. The high point density of the automated system enables precise and accurate mapping of the entire I-V characteristic, including the critical knee region where the maximum power point is located. The conventional method, by contrast, cannot adequately resolve this region due to its insufficient number of data points, resulting in imprecise MPP identification and unreliable parameter extraction.

In terms of curve quality, the Arduino-generated curves exhibit smooth, continuous, and well-defined profiles that closely resemble the theoretical PV characteristics described in the literature. In contrast, the manually obtained curves display an irregular and fragmented shape, a direct consequence of the sparse data collection and the environmental variations that occurred over the extended measurement duration. These quality differences have a direct impact on the accuracy of the extracted parameters, making the automated approach not only faster but also fundamentally more reliable and consistent.

Taken together, these results confirm that the developed system successfully meets its design objectives, offering a low-cost yet high-performance alternative to traditional PV measurement tools, with demonstrated advantages in speed, resolution, and measurement consistency.

4.5 Conclusion:

The experimental work presented in this chapter has successfully demonstrated the validity and effectiveness of the developed low-cost Arduino-based PV analyzer. The system proved capable of generating accurate and well-defined I-V and P-V characteristic curves across a wide range of photovoltaic sources, from a sub-milliwatt small cell to an industrial-grade 80W monocrystalline solar panel, confirming the broad operating range and versatility of the proposed design. The key electrical parameters extracted from each source, including open-circuit voltage, short-circuit current, maximum power point, and fill factor, were found to be physically consistent and in good agreement with the expected theoretical behavior of photovoltaic devices.

The comparative analysis conducted against the conventional manual method using a rheostat and digital multimeter further validated the reliability of the automated system. Both methods yielded consistent values for the fundamental boundary parameters, while the Arduino-based analyzer demonstrated clear and measurable superiority in terms of measurement speed, data resolution, and curve quality. The ability to complete a full characteristic sweep in under one minute, while acquiring more than 2000 data points, represents a significant practical advancement over the time-consuming and low-resolution manual approach.

Overall, the results of this chapter confirm that the developed system successfully fulfills its design objectives as a reliable, accurate, and accessible tool for real-world PV characterization, suitable for both academic research and field applications.

General Conclusion

General Conclusion:

This work set out to design and implement a low-cost Arduino-based photovoltaic analyzer capable of automatically generating accurate I-V and P-V characteristic curves, as a practical alternative to expensive commercial instruments that remain inaccessible to most academic institutions and small-scale laboratories in developing regions.

The developed system successfully achieved its design objectives. By combining an Arduino Mega 2560 microcontroller with an INA219 current and voltage sensor and an MCP4725 12-bit I²C DAC as a direct gate control source, the analyzer demonstrated the ability to characterize photovoltaic sources ranging from a sub-milliwatt small cell to an industrial-grade 80W monocrystalline solar panel, acquiring more than 2000 data points per sweep in under one minute. The comparative evaluation against the conventional rheostat and multimeter method confirmed the reliability and superiority of the proposed system in terms of measurement speed, data resolution, and curve quality.

This project demonstrates that frugal engineering principles can produce scientifically meaningful results, bridging the gap between professional PV measurement tools and the practical needs of educational and field environments. Future developments such as the integration of an MPPT algorithm and wireless monitoring via ESP32 would further extend the capabilities of this system toward a complete and autonomous PV optimization platform.

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