



الجمهورية الجزائرية الديمقراطية الشعبية
People's Democratic Republic of Algeria
وزارة التعليم العالي والبحث العلمي
Ministry of Higher Education and Scientific Research

جامعة وهران 2 محمد بن أحمد
University of Oran 2 Mohamed Ben Ahmed

معهد الصيانة والأمن الصناعي
Institute of Industrial Maintenance and Safety

Department of Instrumentation Maintenance

MASTER THESIS

Submitted in Partial Fulfillment of the Requirements for the Degree of Master

Field: Industrial Engineering

Specialization: Maintenance of Automation and Instrumentation

Thesis Title

Solar Irradiance measurment: Principle and application.

Presented and Publicly Defended by :

BOUCHERIT Khaoula

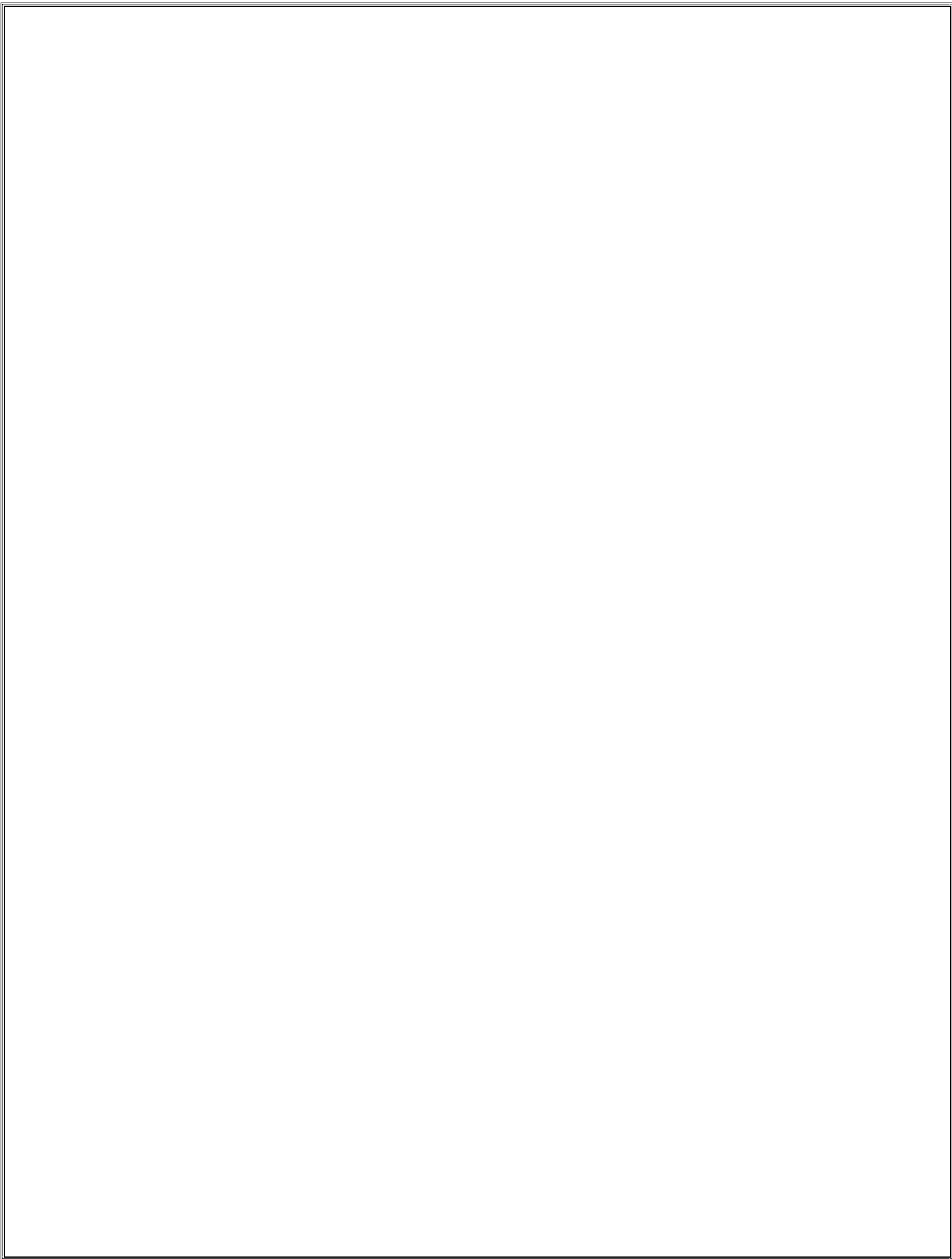
MEDJEBEUR Hadil

Defense Date : 18 july 2026

Before the Examination Committee

Full Name	Academic Rank	Institution	Position
D. GUENDOUZ	Professor	IMSI	President
ABDELATIF HASSINI	Professor	IMSI	Supervisor
A. HADJ KADDOUR	MCB	IMSI	Examiner

Academic Year 2025/2026



KNOWLEDGEMENTS

First and foremost, we must express our deepest gratitude to our supervisor, **Hassini Abdelatif**, for his invaluable guidance, immense patience, and profound technical expertise throughout the development of this research. Their continuous support, insightful criticisms, and engineering advice not only shaped the trajectory of this thesis but also taught us the true rigor of academic research.

We would also like to extend our sincere appreciation to the members of the evaluation committee and the jury for dedicating their time to review this work, and for providing their constructive feedback and evaluations.

Our gratitude also goes to the entire faculty and laboratory staff of the Department of Engineering, whose dedication to education provided us with the solid academic foundation necessary to complete this project.

Finally, words cannot express our profound love and gratitude to our parents, our brother, and our sisters. Their unconditional love, constant encouragement, and endless sacrifices have been our ultimate source of strength and motivation throughout our entire academic journey. To our friends and colleagues who offered their support and companionship, thank you.

DEDICATION

I affectionately dedicate this research work:

To my beloved parents, my mother and my father, for their endless love, prayers, sacrifices, and unconditional support. They have always been my source of strength and motivation, and their guidance has accompanied me throughout every step of my journey.

To my dear sisters soumia ,Hadjer and rodaina, for their constant encouragement, love, and precious presence throughout my life and studies.

To my dear friends Hafsa, Hanaa, Kenza, Wafaa, Chaimaa, Hadjer, Aicha, and Zineb, for their support, companionship, motivation, and the beautiful moments we shared throughout this journey.

To all those who supported me from near or far, I express my deepest gratitude and affection.

Khaoula boucherit .

Abstract

This research presents the design and performance analysis of three low-cost solar irradiance measurement prototypes using accessible electronics. The framework evaluate three topologies interfaced with an Arduino Uno: Method I uses a digital integrated BH1750 (GY-302) sensor over an I²C bus; Method II implements an analog BPW34 PIN photodiode conditioned by an LM358 transimpedance amplifier; Method III deploys a self-sensing reference cell using a 6V mini solar panel connected through a 5:1 voltage divider.

Field data demonstrate distinct operational behaviors.

Method A : showed saturation at midday because the BH1750 sensor reached its upper measurement range under intense sunlight , creating a horizontal clipping flatline at 54,612.50 Lux (546.12 W/m²). Conversely,

Method B : successfully bypassed this digital ceiling through custom gain tuning ($R_f = 100\text{ k}\Omega$), providing continuous analog tracking that reached a peak intensity of 837.00 W/m² at 14:00 without saturation.

Method C : eliminated operational circuit complexity, tracking variations smoothly to a noon peak of 586.32 W/m² (7.04V panel output).

The study concludes that while analog platforms provide the essential broad dynamic range for high-intensity tracking, the encapsulated mini PV panel architecture offers the most balanced physical resilience against regional environmental constraints.

Keywords: Solar Irradiance, Pyranometer, Transimpedance Amplifier, Photodiode, Reference Cell, Arduino Uno.

Résumé

Cette recherche présente la conception et l'analyse des performances de trois prototypes de mesure d'irradiance solaire à bas coût utilisant des composants électroniques accessibles. Le cadre expérimental évalue trois topologies interfacées avec une carte Arduino Uno : La Méthode I utilise un capteur numérique intégré BH1750 (GY-302) via un bus I²C ; La Méthode II implémente une photodiode analogique PIN au silicium BPW34 conditionnée par un amplificateur de transimpédance LM358 ; La Méthode III déploie une cellule de référence auto-captrice utilisant un mini-panneau solaire de 6V adapté par un diviseur de tension de rapport 5:1.

Les données de terrain démontrent des comportements opérationnels distincts.

La Méthode A : a subi une saturation à la mi-journée en raison des limites de son registre 16-bit, créant un écrêtage horizontal plat à 54 612,50 Lux (546,12 W/m²). À l'inverse,

la Méthode B : a contourné ce plafond numérique grâce au réglage du gain ($R_f = 100 \text{ k}\Omega$), permettant un suivi analogique continu qui a atteint un pic de 837,00 W/m² à 14h00 sans saturation.

La Méthode C : a éliminé la complexité des circuits, suivant les fluctuations de manière fluide jusqu'à un pic à midi de 586,32 W/m² (tension brute du panneau de 7,04V).

L'étude conclut que si les plateformes analogiques offrent la plage dynamique indispensable pour la haute intensité, l'architecture du mini-panneau photovoltaïque encapsulé représente le choix le plus équilibré en termes de résilience face aux contraintes environnementales régionales.

Mots-clés : Irradiance Solaire, Pyranomètre, Amplificateur de Transimpédance, Photodiode, Cellule de Référence, Arduino Uno.

ملخص

يقدم هذا البحث تصميم وتشغيل ثلاثة أنظمة منخفضة التكلفة لقياس الإشعاع الشمسي تم تطويرها باستخدام مكونات إلكترونية متاحة. يقيم الإطار التجريبي ثلاثة هياكل متصلة بلوحة (Arduino Uno): الطريقة الأولى تعتمد على مستشعر رقمي مدمج (BH1750 / GY-302) عبر ناقل (I^2C)؛ الطريقة الثانية تنفذ ثنائي ضوئي تناظري (BPW34 PIN) مع مكبر تشغيلي لمقاومة التحويل (LM358)؛ الطريقة الثالثة تعتمد على خلية مرجعية ذاتية الاستشعار باستخدام لوح شمسي صغير بقدرة 6 فولت متصل بمجزئ جهد خافض بنسبة 5:1.

أظهرت البيانات الميدانية سلوكيات تشغيلية متباينة، حيث عانت الطريقة الأولى من تشبع مبكر بسبب قيود السجل الداخلي (16-bit)، مما أدى إلى ثبات خط القياس الأفقي عند 54,612.50 لوكس (546.12 واط/م²) خلال ذروة منتصف النهار. وعلى العكس من ذلك.

نجحت الطريقة الثانية ب في تجاوز هذا السقف الرقمي من خلال ضبط كسب المقاومة ($R_f = 100 \text{ k}\Omega$)، مما وفر تنبؤاً مستمراً وصل إلى ذروة بلغت 837.00 واط/م² عند الساعة 14:00 دون فقدان للبيانات المقاسة.

بينما ألغت الطريقة الثالثة ج تعقيد الدوائر، وتتبع التقلبات بسلاسة لتصل إلى ذروة عند الظهر بلغت 586.32 واط/م² بجهد لوح حقيقي يبلغ 7.04 فولت.

تخلص الدراسة إلى أنه في حين توفر المنصات التماثلية نطاق القياس الديناميكي الواسع والضروري لتتبع الإشعاع عالي الكثافة، فإن بنية اللوح الكهروضوئي الصغير المغلف توفر التوازن الأكثر مرونة ومقاومة ضد القيود البيئية المحلية. الكلمات المفتاحية: الإشعاع الشمسي، بيرانومتر، مكبر مقاومة التحويل، الثنائي الضوئي، الخلية المرجعية، أردوينو.

TABLE OF CONTENTS

General Introduction.....	1
Chapter 1	4
Theoretical Foundations of Solar Radiation	4
1.1. Introduction.....	5
1.2. Definition of Solar Radiation	6
1.2.1. Solar Irradiance (G).....	7
1.2.2. Solar Irradiation (H).....	7
1.2.3. Comparison and Significance.....	8
1.3. Nature of Solar Radiation	8
1.3.1. The Solar Spectrum	9
1.3.2. Spectral Energy Distribution	10
1.4. Types of Solar Radiation	11
1.4.1. Direct (Beam) Radiation	11
1.4.2. Diffuse Radiation	11
1.4.3. Reflected Radiation (Albedo).....	12
1.4.4. Global Radiation.....	12
1.5. The Solar Constant.....	13
1.5.1. Definition and Standard Value	13
1.5.2. Variations in Solar Intensity	14
1.5.3. Mathematical Representation of Daily Variation	14
1.6. Factors Influencing Solar Irradiance	15
1.6.1. Solar Geometry and the Air Mass (AM) Concept.....	15
1.6.2. Geographical Location: Latitude and Altitude	16
1.6.3. Atmospheric Composition and Turbidity	17
1.6.4. Cloud Cover and Seasonality	17
1.7. Interaction with the Atmosphere	18
1.7.1. Absorption Mechanisms	18
1.7.2. Scattering (Diffusion).....	19
1.7.3. Reflection and the Concept of Albedo	19
1.7.4 The Beer-Lambert Law of Extinction	20
1.8. Importance of Solar Radiation	20

1.8.1.	Driving the Earth's Climatic System.....	21
1.8.2.	The Biological Foundation: Photosynthesis.....	21
1.8.3.	Energy Security and the National Strategy.....	21
1.8.4.	Impact on Materials and Industrial Infrastructure.....	22
1.9.	Applications of Solar Radiation.....	22
1.9.1.	Photovoltaic (PV) Energy Conversion	233
1.9.2.	Solar Thermal Systems (Low and Medium Temperature).....	24
1.9.3.	Concentrated Solar Power (CSP).....	25
1.9.4.	Solar Desalination	26
1.9.5.	Space and Satellite Applications	26
1.9.6.	Bioclimatic Architecture and Passive Solar Design	26
1.10.	Conclusion	27
Chapter 2		28
Instruments and Techniques for Solar Irradiance Measurement		28
2.1.	Introduction.....	29
2.2.	Solar Measurement Strategies	30
2.2.1.	Categorization of Measurement Methods.....	30
2.2.2.	Key Functional Requirements for a Measurement System	30
2.2.3.	The Choice for Local Design	31
2.3.	Standard Meteorological Instrumentation (The Professional Path).....	31
2.3.1.	The Pyranometer.....	31
2.3.2.	The Pyrhelimeter	33
2.3.3.	Advantages and Constraints of Professional Instruments	34
2.3.4.	Calibration and Traceability of Professional Sensors	35
2.3.5.	Sources of Measurement Errors and Uncertainties.....	36
2.4.	Low-Cost Design Architectures (The Custom Path)	38
2.4.1.	Method A: Digital Integrated Sensing (BH1750)	40
2.4.2.	Method B : Analog Photodiode Sensing (BPW34)	38
2.4.3.	Method C: Mini-PV Characterization (Solar Panel as Sensor)	41
2.4.4.	Data Acquisition and Processing System (DAQ)	42
2.4.5.	Discussion and Justification of Choice	44
2.5.	Detailed Study of Components (Technical Data Sheets)	45

2.5.1.	Silicon PIN Photodiode (BPW34)	45
2.5.2.	Digital Light Sensor (BH1750FVI)	46
2.5.3.	Operational Amplifier (LM358).....	46
2.5.4.	Voltage Sensor Module (5:1 Resistive Divider)	47
2.5.5.	CurrentSensor (ACS712)	48
2.5.6.	The Processing Core (Arduino Nano/Uno).....	48
2.6.	Conclusion.....	49
Chapter 3		50
Design, Implementation and Performance Evaluation of the Proposed Methods.....		50
3.1.	Introduction.....	51
3.2.	Experimental Implementation of Method A: The Digital Integrated Platform (BH1750 / GY-302).....	53
3.2.1.	Hardware Configuration and I ² C Pin Mapping	53
3.2.2.	Firmware Architecture and Digital Signal Filtering	55
3.2.3.	Empirical Calibration Factor Optimization.....	57
3.2.4.	Meteorological Field Logging Data (May 22, 2026).....	58
3.3.	Experimental Implementation of Method B: The Analog Transimpedance Photodiode Platform (BPW34 + LM358)	59
3.3.1.	Hardware Engineering and Circuit Assembly	60
3.3.2.	Analog Signal QuantizationFirmware	62
3.3.3.	Empirical Data Analysis and Irradiance Tracking.....	65
3.4.	Experimental Implementation of Method C: The Self-Sensing Mini Photovoltaic Panel Platform.....	67
3.4.1.	Engineering Principles of Open-Circuit Voltage Sensing	67
3.4.2.	Physical Interfacing and Pin Topologies	68
3.4.3.	Meteorological Field Logging Data (May 26, 2026)	72
3.5.	Advanced Diagnostic Analysis: Digital Saturation vs. Analog Linear Continuity .	74
3.5.1.	The Digital Sensor Saturation Bottleneck.....	74
3.5.2.	Mathematical Proof of Unsigned 16-Bit Register Clipping	75
3.5.3.	Evaluation of Photodiode and Reference Cell Linear Continuity	76
3.6.	Hardware Synthesis, Structural Uncertainties, and Constraints	77
3.6.1.	Inherent System Uncertainties and Environmental Variables	78
3.6.2.	Engineering Evaluation Matrix.....	79

3.7. Conclusion.....	81
General Conclusion	81
Bibliography	87
Annexes	87

List of figures

Chapter 1:

Figure 1.1 Schematic of solar radiation	6
Figure 1.2 Solar Radiation Spectrum.....	9
Figure 1.3 schematic of Types of Solar Radiation	10
Figure 1.4 the monthly distribution of average daily solar irradiation	12
Figure 1.5 Air Mass (AM) geometric concept	15
Figure 1.6 Explanation of Photovoltaic Work.....	23
Figure 1.7 Solar Water Heating	24
Figure 1.8 concentrated solar power types.....	25

Chapter 2:

Figure 2.1 pyranometer	32
Figure 2.2 The Pyrheliometer	33
Figure 2.3 A schematic illustration of a pyranometer (a) and a pyrheliometer (b).....	34
Figure 2.4 NOYITO BH1750 Digital Light Intensity Sensor	39
Figure 2.5 BPW34 Photodiode And Pinout.....	41
Figure 2.6 Wiring diagram showing the voltage sensor module connected to Arduino UNO	42
Figure 2.7 LM358	46
Figure 2.8 Voltage Sensor Module (5:1 Resistive Divider)	47
Figure 2.9 Arduino Uno	48

Chapter 3:

Figure 3.1 General synoptic Schema of the experimental methodology and solar data acquisition chains	52
Figure 3.2 Physical prototype assembly and breadboard wiring layout of the unshielded digital BH1750 light sensor module interfaced with the Arduino Uno development core.....	54

Figure 3.3 Synoptic Block diagram (Method A)	54
Figure 3.4 Synoptic Block Diagram (Method B).....	60
figure 3.5 Component-level breadboard implementation of the analog BPW34 PIN photodiode conditioned via an external active LM358 transimpedance operational amplifier circuit.	62
Figure 3.6 Physical prototype assembly and breadboard wiring layout of the unshielded digital for Voltage Sensor	70
Figure 3.7 Synoptic Block Diagram (Method C)	70

List of tables

Chapter 1:

Table 1.1 Technical Comparison between Irradiance and Irradiation.....	8
Table 1.2 Energy Distribution of the Solar Spectrum	10

Chapter 2:

Table 2.1 Comparison of Pyranometers vs. Pyrhemimeters	35
Table 2.2 Comparative Matrix of Solar Measurement Techniques	44

Chapter 3:

Table 3.1 Hourly Climatic Metrics for Method A (May 22, 2026)	58
Table 3.2 Quantized Hourly Records for Method B Analog Architecture	65
Table 3.3 Quantized Hourly Records for Method C Photovoltaic Self-Sensing Architecture	73
Table 3.4 Engineering Synthesis and Comparison Matrix of Prototyped Systems.....	80

General

Introduction

The global transition toward sustainable energy has positioned solar energy as one of the most vital resources for long-term energy security and climate mitigation. For Algeria, situated in the heart of the "Solar Belt," solar energy is a strategic priority. With annual sunshine exceeding 3,500 hours in the Sahara, the nation's renewable energy program aims to install 15,000 MW of capacity by 2035 to preserve natural gas reserves for future generations.

Harnessing this immense potential requires a deep scientific and empirical understanding of the resource. Solar radiation is a complex, intermittent phenomenon influenced by Earth's orbital dynamics, local geography, and atmospheric interactions such as absorption and scattering. For engineers, accurately distinguishing between the direct, diffuse, and global components of radiation is essential for the optimization, performance modeling, and economic assessment of solar power systems.

While utility-scale solar asset mapping traditionally relies on satellite-derived modeling or high-precision meteorological instruments like thermopile pyranometers, independent researchers face significant barriers. High-end certified sensors require extreme financial investments, specialized data loggers, and intensive daily maintenance to prevent major measurement errors caused by dust and environmental soiling. This technical bottleneck creates a pressing need for low-cost, decentralized ground-level measurement frameworks that leverage mass-produced consumer electronics and microcontrollers.

The core objective of this master's thesis is to bridge the gap between theoretical atmospheric formulations and practical instrumentation by designing, building, and field-testing alternative solid-state solar monitoring architectures. By evaluating different solid-state sensing technologies under identical meteorological conditions, this study systematically analyzes the operational limits, noise immunity, dynamic range constraints, and structural uncertainties of alternative low-cost instrumentation pathways.

To achieve these objectives, the research is organized into three technical chapters:

- Chapter 1 establishes the theoretical foundations of solar radiation, defining physical parameters, atmospheric extinction mechanisms, and the state of the national energy strategy in Algeria.
- Chapter 2 explores established meteorological measurement strategies, comparing standard industrial instrumentation against low-cost prototyping architectures to justify the hardware design choices.
- Chapter 3 details the physical assembly, firmware implementation, and empirical field deployment results of three specific built multi-prototype platforms: the Digital Integrated Platform (Method A), the Analog Transimpedance Photodiode Platform (Method B), and the Self-Sensing Photovoltaic Reference Cell Platform (Method C), culminating in an advanced diagnostic analysis of their performance limits.

Chapter 1

Theoretical Foundations

of Solar Radiation

1.1. Introduction

The global transition toward sustainable energy has positioned solar radiation as the most vital resource for long-term energy security and climate mitigation [1]. For Algeria, situated in the heart of the "Solar Belt," solar energy is a strategic priority. With annual sunshine exceeding 3,500 hours in the Sahara, the nation's renewable energy program aims to install 15,000 MW of capacity by 2035 to preserve natural gas reserves for future generations [1] [2].

Harnessing this immense potential requires a deep scientific understanding of the resource. Solar radiation is a complex, intermittent phenomenon influenced by Earth's orbital dynamics, local geography, and atmospheric interactions such as absorption and scattering. For engineers, accurately distinguishing between the direct, diffuse, and global components of radiation is essential for the optimization and economic assessment of solar power systems.

This chapter establishes the theoretical foundations of solar radiation. It defines the physical concepts of irradiance and irradiation, examines the spectral distribution of solar energy, and analyzes the environmental factors that dictate solar availability within the Algerian territory. By providing this base, we set the stage for the practical measurement techniques and instrumentation discussed later in this work.

1.2. Definition of Solar Radiation

Solar radiation is the energy emitted by the sun in the form of electromagnetic waves. This radiation travels through the vacuum of space at the speed of light ($C \approx 3 \times 10^8 \text{ m/s}$) and serves as the primary energy input for the Earth's climate and energy systems. To analyze this energy for engineering purposes, it is fundamental to distinguish between the power received at a specific moment and the total energy accumulated over time [1].

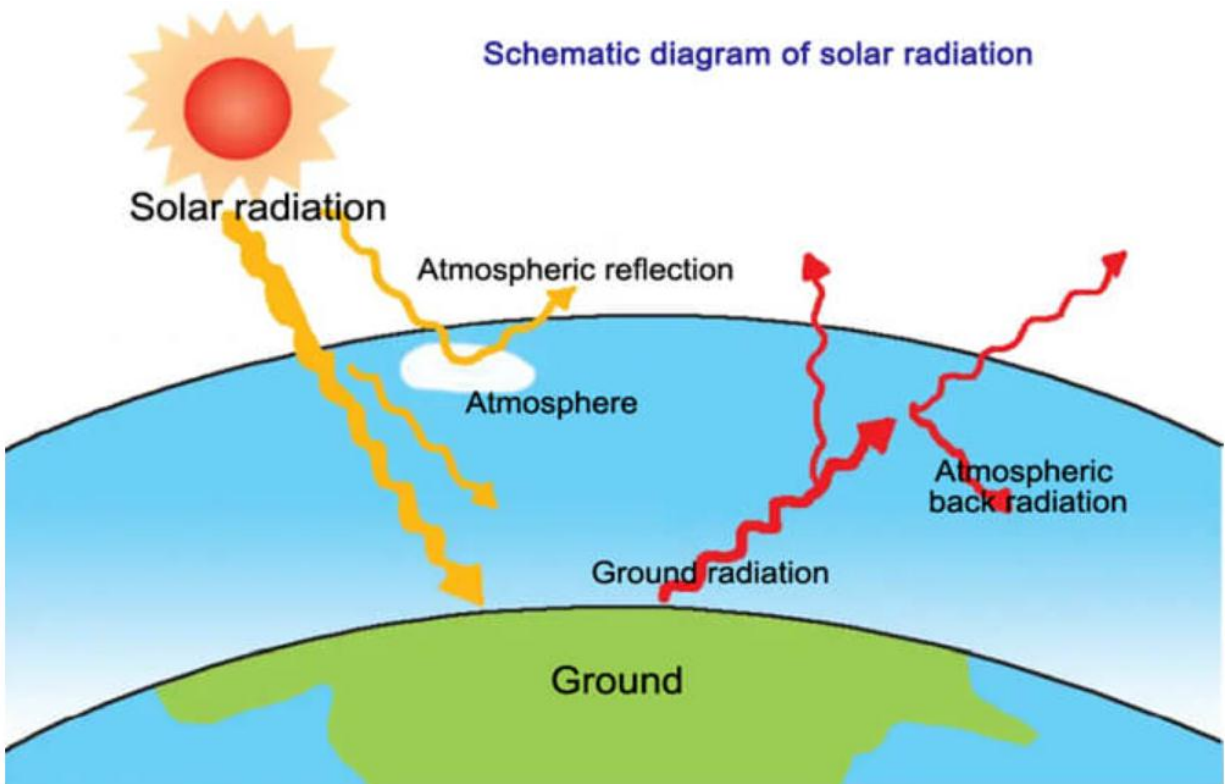


Figure 1.1 Schematic of solar radiation [3]

1.2.1. Solar Irradiance (G)

Solar Irradiance (1.1) is defined as the instantaneous power of solar radiation per unit area. It represents the intensity of the sun at a specific second.

- Symbol: G (sometimes denoted as I).
- Unit: Watts per square meter (W/m^2).
- Physical Meaning: It indicates how much solar power is hitting a surface (like a photovoltaic panel) right now.
- Measurement: It is typically measured using an instrument called a pyranometer.

The formula for irradiance (1.1) is given by:

$$G = \frac{dP}{dA} \quad (1.1)$$

Where:

- G is the Irradiance (W/m^2).
- P is the Power (W).
- A is the Area (m^2).

In the Algerian Sahara, the peak irradiance at solar noon can reach or even exceed 1000 W/m^2 under clear sky conditions, which is the standard value used for rating solar panels (STC - Standard Test Conditions) [2].

1.2.2. Solar Irradiation (H)

Solar Irradiation (or solar insolation) (1.2) is the total amount of solar energy received per unit area over a specific period, such as an hour, a day, or a month. It is the integral of irradiance over time.

- Symbol: H.
- Unit: Watt-hours per square meter (Wh/m^2) or Mega-Joules per square meter (MJ/m^2). In Algerian meteorological reports, it is often expressed in $\text{kWh/m}^2/\text{day}$.

- **Physical Meaning:** It tells us the total energy yield. This is the value used to calculate how much electricity a battery can store over a full day of sunshine.

The mathematical relationship between irradiation and irradiance is:

$$H = \int_{t_1}^{t_2} G dt \quad (1.2)$$

1.2.3. Comparison and Significance

Understanding the difference between these two parameters is crucial for solar engineering. While **Irradiance** determines the peak capacity of the equipment (like the size of the inverter), **Irradiation** determines the total energy production and the economic return of the project.

Tableau 1.1 *Technical Comparison between Irradiance and Irradiation*

Feature	Solar Irradiance (G)	Solar Irradiation (H)
Physical Quantity	Power Density	Energy Density
Time Factor	Instantaneous (per second)	Cumulative (per hour/day/year)
SI Unit	W/m ²	J/m ² or Wh/m ²
Engineering Use	Sizing cables and inverters	Calculating total electricity yield
Algerian Data Source	Real-time monitoring stations	Historical databases (e.g., NASA Power, CDER Atlas)

1.3. Nature of Solar Radiation

Solar radiation (1.3) is electromagnetic in nature, meaning it consists of oscillating electric and magnetic fields that transport energy through the vacuum of space. According to electromagnetic theory, this radiation behaves both as waves and as particles called "photons" [3]. The energy of a photon is inversely proportional to its wavelength (λ):

$$E = \frac{(h \times c)}{\lambda} \quad (1.3)$$

Where:

- E : is the photon energy.
- h : is Planck's constant.
- c : is the speed of light.
- λ : (Lambda) is the wavelength.

1.3.1. The Solar Spectrum

The radiation emitted by the sun covers a wide range of wavelengths, but the majority of the energy reaching the Earth's surface is concentrated in the optical range (100 nm to 4000 nm). This spectrum is typically divided into three primary bands:

- Ultraviolet (UV) Radiation (100–400 nm): This band contains high-energy photons but represents only a small fraction (about 5%) of the total solar energy. Most UV rays are absorbed by the Earth's ozone layer [2]
- Visible Light (400–700 nm): This is the part of the spectrum that the human eye can perceive. It is the most intense part of the solar radiation (about 45%) and is highly efficient for photovoltaic conversion.
- Infrared (IR) Radiation (> 700 nm): Primarily felt as heat, infrared radiation accounts for nearly half of the total energy (about 50%) and is responsible for the thermal effects observed in solar collectors [3].

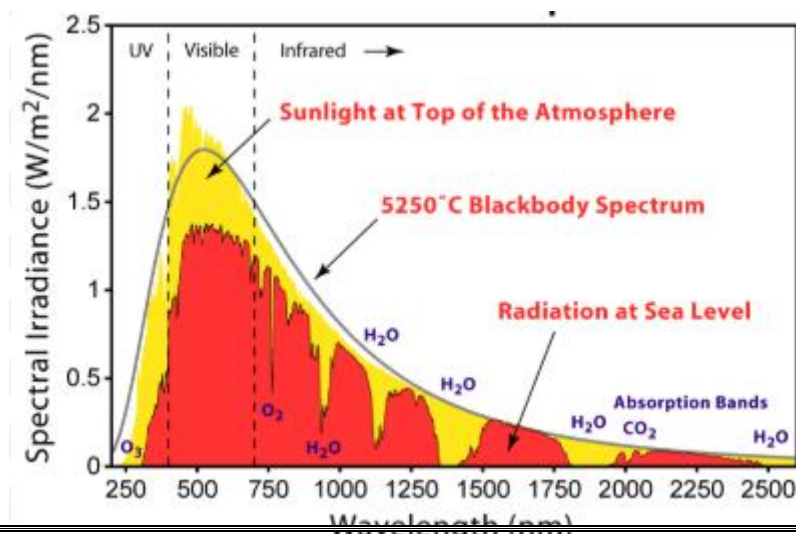


Figure 1.2 Solar Radiation Spectrum [11]

1.3.2. Spectral Energy Distribution

The distribution of energy across these bands varies depending on whether the measurement is taken outside the atmosphere or at ground level. At ground level, the AM1.5 (Air Mass 1.5) spectrum is used as the universal standard for testing solar equipment [8].

Tableau 1.2 Energy Distribution of the Solar Spectrum

Spectral Band	Wavelength Range (nm)	Energy Percentage (%)
Ultraviolet (UV)	100 – 400	~5%
Visible Light	400 – 700	~45%
Infrared (IR)	700 – 4000	~50%

In Algeria, research conducted by the CDER emphasizes that the high clarity of the sky in the Saharan regions results in a higher reception of the visible component compared to the more humid coastal North [2].

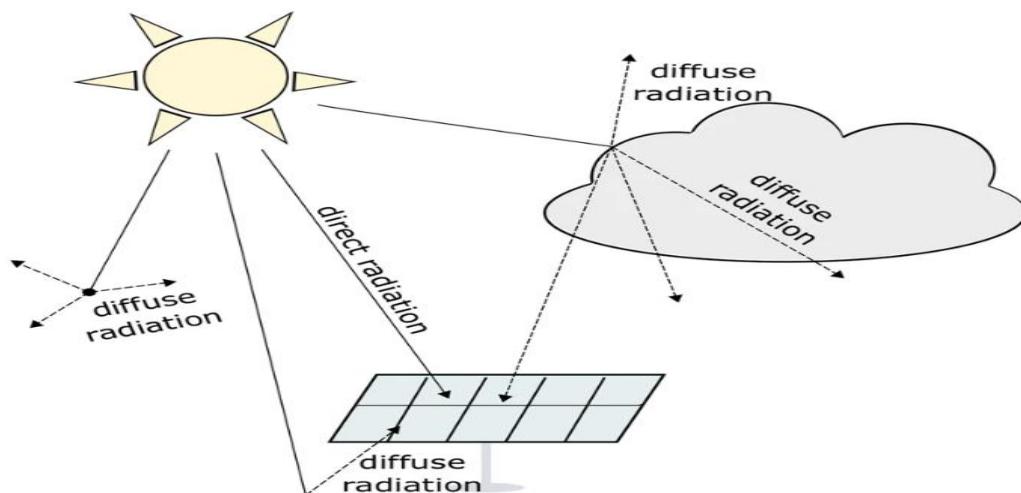


Figure 1.3 Schematic of Types of Solar Radiation [11]

1.4. Types of Solar Radiation

When solar radiation travels through the Earth's atmosphere, it undergoes various physical interactions such as scattering, absorption, and reflection. These interactions split the incoming solar flux into distinct components. In solar engineering, understanding these types is essential because different technologies—such as Photovoltaic (PV) panels and Concentrated Solar Power (CSP) systems—rely on different parts of the solar spectrum to operate efficiently [1] [3].

1.4.1. Direct (Beam) Radiation

Direct radiation, also known as beam radiation, consists of solar rays that travel in a straight line from the sun's disk to the Earth's surface without being diverted by the atmosphere. It is the most intense component of solar energy and is responsible for casting sharp, defined shadows.

Direct radiation is the primary energy source for Concentrated Solar Power (CSP) plants, which use mirrors to focus light. In the clear, arid skies of the Algerian Sahara, such as the Adrar and Tamanrasset regions, the direct component is exceptionally high, often making up more than 70% of the total energy received at ground level [2].

1.4.2. Diffuse Radiation

Diffuse radiation is the solar energy that reaches the ground after being scattered by atmospheric molecules (Rayleigh scattering) or by larger particles like clouds, dust, and water vapor (Mie scattering). This component does not come from a single point but rather from the entire sky vault.

Diffuse radiation does not produce shadows and is multi-directional. On a completely cloudy day, almost 100% of the solar radiation reaching the ground is diffuse. While CSP systems cannot utilize this light, standard PV panels can still capture diffuse radiation to generate electricity, which is why they continue to function during overcast weather.

1.4.3. Reflected Radiation (Albedo)

Reflected radiation is the portion of solar energy that bounces off the ground or nearby surfaces (such as sand, buildings, or water) before hitting a solar collector. The reflectivity of a surface is known as its "Albedo."

In Algeria, the high reflectivity of desert sands provides a significant albedo effect. This is particularly important for "Bifacial" solar panels, which are designed to capture light on both their front and rear surfaces. By utilizing the radiation reflected from the ground, these systems can significantly increase their total energy output in desert environments [2]

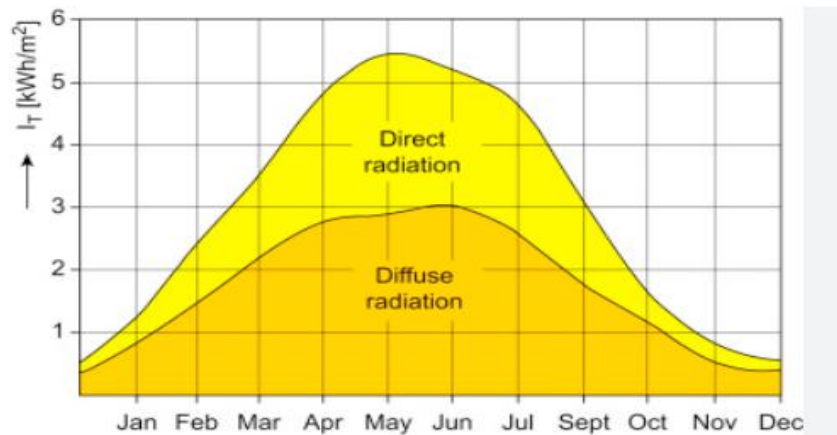


Figure 1.4 the monthly distribution of average daily solar irradiation [3]

1.4.4. Global Radiation

Global radiation (1.4) is the total amount of solar energy received on a horizontal surface. It is the summation of the direct, diffuse, and reflected components. The intensity of global radiation is heavily influenced by the "Solar Zenith Angle" (Theta), which is the angle between the sun's position and the vertical line directly above the observer.

The relationship between these components is defined by the following fundamental equation:

$$G_{\text{(global)}} = (G_{\text{(direct)}} \times \cos(\theta)) + G_{\text{(diffuse)}} + G_{\text{(reflected)}} \quad (1.4)$$

Where:

- G_{global} is the Total Global Irradiance (W/m^2).
- G_{direct} is the Direct Beam Irradiance (W/m^2).
- Theta (θ) is the solar zenith angle (the angle between the sun and the vertical).
- G_{diffuse} is the Diffuse Sky Irradiance (W/m^2).
- $G_{\text{reflected}}$ is the Ground-reflected Irradiance (W/m^2)

1.5. The Solar Constant

The amount of solar energy reaching the Earth is remarkably stable when measured outside the influence of the atmosphere. This baseline value is a fundamental parameter in solar science and is known as the Solar Constant. It represents the maximum possible energy available at the distance of the Earth before any atmospheric losses occur [1].

1.5.1. Definition and Standard Value

The solar constant is defined as the amount of solar electromagnetic radiation per unit area that would be incident on a plane perpendicular to the rays at a distance of one Astronomical Unit (AU) from the Sun. An AU is the mean distance between the Sun and the Earth.

Based on high-precision satellite measurements, the internationally accepted average value for the solar constant is:

$$G_{\text{sc}} = 1361 \text{ W/m}^2$$

While older literature often cited a value of 1367 W/m^2 , modern data from satellite missions (such as the SORCE and TSIS-1 missions) have refined this value to 1361 W/m^2 . This energy flux is measured at the "Top of the Atmosphere" (TOA), where there is no interference from clouds, dust, or air molecules. This value is used by researchers at the CDER as a reference point to calculate the efficiency of the Algerian atmosphere in letting solar energy pass through to the surface [4].

1.5.2. Variations in Solar Intensity

Although it is termed a "constant," the actual amount of solar radiation reaching the top of the atmosphere fluctuates throughout the year. These fluctuations are primarily caused by the Earth's elliptical orbit around the sun rather than changes in the sun's output itself.

- a) Earth-Sun Distance: The distance between the Earth and the Sun varies by about 3.3%. The Earth is closest to the Sun (Perihelion) in early January and furthest away (Aphelion) in early July. This variation causes the extraterrestrial irradiance to fluctuate between approximately 1322 W/m² and 1412 W/m² throughout the year.
- b) Solar Activity Cycles: The Sun undergoes periodic cycles of activity, most notably the 11-year sunspot cycle. These cycles cause minor variations in the total solar irradiance, typically on the order of 0.1%. While small, these variations are monitored by meteorological organizations to improve long-term climate models.

1.5.3. Mathematical Representation of Daily Variation

To calculate the exact extraterrestrial radiation (G_{on}) (1.5) on any given day of the year (n), engineers use a formula to account for the orbital eccentricity. This is crucial for precise simulation of solar power plant performance over a full year.

The formula is expressed as:

$$G_{on} = G_{sc} \times (1 + 0.033 \times \cos(360 \times n / 365)) \quad (1.5)$$

Where:

- G_{on} : the extraterrestrial radiation for a specific day (W/m²).
- G_{sc} : the Solar Constant (1361 W/m²).
- n : the day of the year, ranging from 1 (January 1st) to 365 (December 31st).

By understanding this theoretical maximum, Algerian engineers can determine the "Clearness Index" (K_t), which is the ratio of the radiation measured on the ground to the

radiation available at the top of the atmosphere. A high clearness index is a signature of the Saharan climate, where atmospheric losses are minimized [2].

1.6. Factors Influencing Solar Irradiance

The quantity and quality of solar energy reaching a specific location on the Earth's surface are never uniform. Solar irradiance is subject to constant fluctuations caused by a complex interaction between the Earth's orbital dynamics, the geographical characteristics of the site, and the physical state of the atmosphere. For engineers in Algeria, a deep understanding of these factors is critical for the accurate sizing, performance modeling, and economic forecasting of solar energy systems [1] [2].

1.6.1. Solar Geometry and the Air Mass (AM) Concept

The most significant factor influencing the intensity of ground-level irradiance is the position of the sun relative to the observer, which changes throughout the day and the year. This position is primarily defined by the Solar Zenith Angle (θ), the angle between the sun's rays and the vertical line directly above the observer.

When the sun is at its peak (solar noon), the zenith angle is at its minimum, and the rays travel the shortest possible distance through the atmosphere. As the sun moves toward the horizon, the path length of the rays through the air increases. This physical

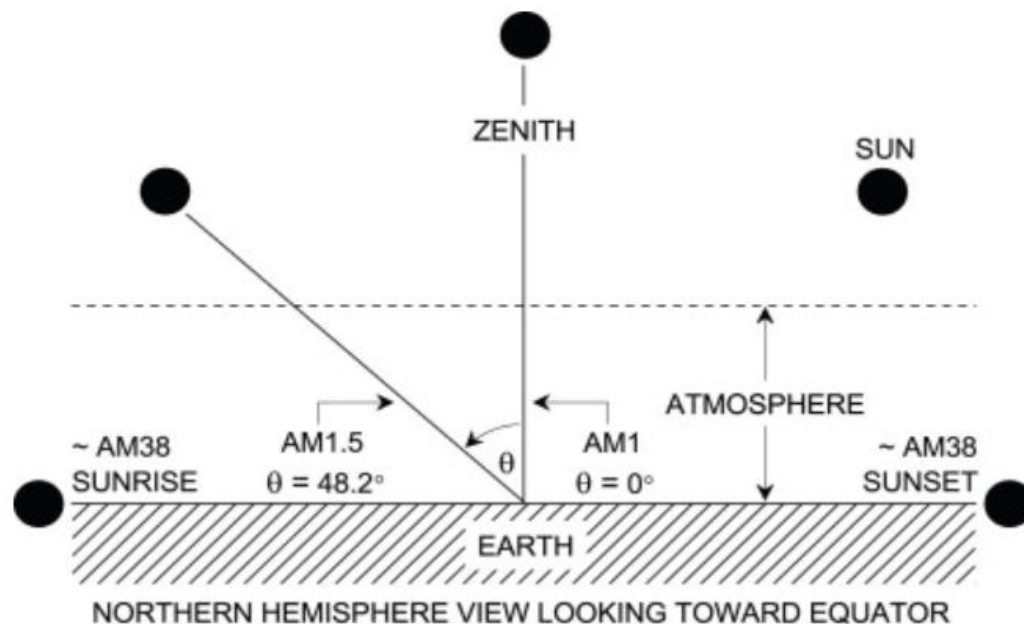


Figure 1.5 Air Mass ($\bar{A}M$) geometric concept [3]

path length is quantified by a dimensionless term known as the Air Mass (AM).

The standard mathematical relationship for Air Mass, assuming a flat atmosphere, is:

$$AM = 1 / \cos (\theta) \quad (1.6)$$

Where:

- AM is the Air Mass.
- Theta is the Solar Zenith Angle in degrees.

In the vacuum of space, the Air Mass is AM 0. When the sun is directly overhead at sea level, it is AM 1.0. For international standardization in testing solar photovoltaic modules, the AM 1.5 spectrum is used, representing a zenith angle of 48.2 degrees. In Algeria, the Air Mass values change drastically from sunrise to midday, directly affecting the spectral distribution and the power output of solar arrays [1].

1.6.2. Geographical Location: Latitude and Altitude

The coordinates of a project site determine the theoretical maximum solar energy it can receive:

- a) Latitude: This coordinate determines the angle of incidence of the sun's rays throughout the different seasons. Algeria is located between latitudes 19 degrees N and 37 degrees N. The southern regions (lower latitudes) generally receive more concentrated energy because the sun remains higher in the sky for a longer duration. In the North (higher latitudes), the sun stays lower, leading to more atmospheric scattering.
- b) Altitude: At higher elevations, the atmosphere is thinner and cleaner. Locations in the Aurès Mountains or the High Plateaus (such as Tiaret, Setif, or Djelfa) receive significantly higher irradiance than coastal cities at sea level. This is because there is a smaller volume of air, less water vapor, and fewer pollutants to absorb the incoming light [2] [5].

1.6.3. Atmospheric Composition and Turbidity

The Earth's atmosphere acts as a selective filter that attenuates (weakens) solar radiation through two main processes: absorption and scattering.

- **Gaseous Absorption:** Specific atmospheric gases absorb energy at certain wavelengths. For example, the Ozone layer in the stratosphere absorbs the majority of high-energy Ultraviolet (UV) rays, while Water Vapor (H₂O) and Carbon Dioxide (CO₂) absorb significant portions of the Infrared (IR) spectrum.
- **Atmospheric Turbidity (Aerosols):** Turbidity describes the haziness of the sky caused by suspended solid or liquid particles (aerosols). In the Algerian context, Saharan Dust is a major factor. Frequent sandstorms and the presence of fine mineral dust in the air scatter the direct solar beam, converting it into diffuse radiation. This phenomenon, often studied by the CDER, can reduce the direct irradiance by over 30% during high-dust events, which is a critical consideration for Concentrated Solar Power (CSP) plants [6].

1.6.4. Cloud Cover and Seasonality

Cloud cover is the most volatile and unpredictable factor in solar measurement. Depending on their thickness and type, clouds can reflect and absorb up to 90% of incident radiation, causing rapid "ramping" events where power output drops suddenly.

Seasonality is driven by the Earth's axial tilt of 23.45 degrees. This tilt causes the sun path to be much higher in the summer than in the winter. In Algeria, the daily Solar Irradiation (total energy sum) is significantly higher in June than in December. In the Sahara, however, the clarity of the sky and the lower latitude ensure that even winter irradiation remains high enough for productive solar harvesting [3].

1.7. Interaction with the Atmosphere

The solar radiation that reaches the top of the Earth's atmosphere does not arrive at the ground level intact. As the electromagnetic waves travel through the various layers of the atmosphere—the troposphere, stratosphere, and mesosphere—they undergo a process known as Atmospheric Extinction or attenuation. This process is the result of three fundamental physical mechanisms: absorption, scattering, and reflection. For researchers in Algeria, analyzing these interactions is vital to understanding the local "clearness index" and the spectral quality of light available for energy conversion [1].

1.7.1. Absorption Mechanisms

Absorption is the process by which atmospheric gases take up solar energy and convert it into internal thermal energy or chemical energy. This process is highly "wavelength-selective," meaning specific gases only absorb specific parts of the solar spectrum.

The Ozone Layer (O_3): Located primarily in the stratosphere, ozone is the Earth's primary shield against high-energy radiation. It absorbs nearly 100% of lethal Ultraviolet-C (UVC) rays and a large majority of Ultraviolet-B (UVB) rays. Without this absorption, the high-energy photons would cause significant degradation to solar cell materials and biological tissues [4].

Water Vapor (H_2O): This is the most significant absorber in the Infrared (IR) region. Water vapor creates "absorption bands" that block specific wavelengths of heat energy. In the humid coastal regions of Northern Algeria, such as Oran or Algiers, the absorption by water vapor is much higher than in the dry Saharan interior [2].

Carbon Dioxide (CO_2) and Oxygen (O_2): These gases also contribute to the absorption of infrared and extreme ultraviolet radiation, respectively. The cumulative effect of these gases creates what scientists call "Atmospheric Windows"—specific ranges of wavelengths where the atmosphere is transparent and allows solar energy to pass through with minimal loss.

1.7.2. Scattering (Diffusion)

Scattering occurs when solar photons collide with air molecules or suspended particles, causing them to be redirected in all directions. This physical phenomenon is responsible for the creation of Diffuse Radiation. There are two primary types of scattering that affect the Algerian sky:

- Rayleigh Scattering: This occurs when the particles (primarily Nitrogen and Oxygen molecules) are much smaller than the wavelength of the incident light. Rayleigh scattering is more effective at shorter wavelengths, which is why the sky appears blue. This process contributes significantly to the diffuse light captured by solar panels even on clear days [1].
- Mie Scattering: This occurs when the atmospheric particles are of a similar size to the wavelength of light. These particles, known as aerosols, include smoke, water droplets, and—most importantly for Algeria—Saharan Dust. Mie scattering is less wavelength-dependent and tends to scatter light in a forward direction, creating a "haze" around the sun. During "Sirocco" wind events in Algeria, Mie scattering becomes the dominant factor, drastically reducing the direct beam of the sun while increasing the diffuse component[5].

1.7.3. Reflection and the Concept of Albedo

A significant portion of incoming solar energy is reflected back into space before it can reach the ground. The primary reflectors are clouds, which can reflect between 40% and 90% of incident light depending on their thickness and water content.

However, once the radiation reaches the ground, another form of reflection occurs between the Earth's surface and the solar collector. This is quantified by the Albedo (ρ), which is the ratio of reflected radiation to incident radiation.

$$\text{Albedo } (\rho) = \frac{\text{Reflected Radiation}}{\text{Incident Radiation}} \quad (1.7)$$

In solar engineering, ground albedo is a critical parameter for tilted photovoltaic systems. In the Algerian Sahara, the light-colored, quartz-rich sands have a high albedo (1.7) (approx. 0.35 to 0.45) compared to the darker soils of the North (approx. 0.15 to 0.20). This reflected energy provides an additional power boost for solar panels, especially modern bifacial modules that capture light from both sides .

1.7.4. The Beer-Lambert Law of Extinction

To mathematically model the reduction of solar intensity as it passes through the atmosphere, engineers use the Beer-Lambert Law. This law states that the intensity of the direct beam decreases exponentially with the atmospheric path length (Air Mass).

The simplified formula for terrestrial irradiance (G_{ter}) is:

$$G_{ter}(k, AM) = G_{on} \cdot e^{-k \cdot AM} \quad (1.8)$$

Where:

- G_{ter} : the irradiance at the Earth's surface (W/m^2).
- G_{on} : the extraterrestrial radiation (W/m^2).
- k : the atmospheric extinction coefficient (determined by turbidity and humidity).
- AM : the Air Mass.

This equation is the mathematical (1.8) foundation for all solar resource assessment software used by the CDER and other international energy agencies to map the solar potential of the Algerian territory [2].

1.8. Importance of Solar Radiation

Solar radiation is far more than just a source of electricity; it is the fundamental energy engine that powers almost every physical, chemical, and biological process on our planet. For a nation like Algeria, the importance of this radiation is multifaceted, spanning from environmental stability to strategic economic independence. Understanding its significance is the first step in justifying the massive investments required for the transition to a solar-based economy [1] [7].

1.8.1. Driving the Earth's Climatic System

Solar radiation is the primary driver of the Earth's climate and weather patterns. The uneven heating of the Earth's surface by the sun creates pressure differences in the atmosphere, which in turn generate wind patterns. Furthermore, solar energy powers the global hydrological cycle by driving the evaporation of water from oceans and lakes, leading to cloud formation and precipitation.

In the North African context, solar radiation levels directly influence the rate of evapotranspiration. For Algeria, this is a critical factor in managing water scarcity and combating desertification. The high intensity of solar exposure in the Sahara helps regulate the "Thermal Lows" that influence the seasonal movement of the Intertropical Convergence Zone (ITCZ), affecting rainfall across the continent [2].

1.8.2. The Biological Foundation: Photosynthesis

From a biological perspective, solar radiation is the ultimate source of life. Through the process of photosynthesis, green plants, algae, and certain bacteria capture photons to convert carbon dioxide and water into organic compounds (glucose) and oxygen.

This process is the foundation of the global food chain. Without the specific visible spectrum of solar radiation, primary production would cease, leading to the collapse of all ecosystems. Furthermore, the solar energy captured by plants millions of years ago is what created the fossil fuels (oil, gas, and coal) that power the modern world today. Thus, by shifting to solar power, we are simply bypassing the millions of years of "storage" and harvesting the energy directly at its source [3].

1.8.3. Energy Security and the National Strategy

For Algeria, solar radiation represents a "strategic insurance policy." As a country traditionally dependent on hydrocarbon exports (oil and gas), the transition to solar energy is essential to preserve natural gas reserves for future generations and for high-value petrochemical industries.

The Algerian National Renewable Energy Program aims to exploit the country's vast solar potential to achieve a capacity of 15,000 MW by 2035. This is not merely an

environmental goal but a socio-economic necessity to meet the rising domestic demand for electricity, which is growing at an average rate of 5% to 7% annually [7].

1.8.4. Impact on Materials and Industrial Infrastructure

The importance of solar radiation also extends to engineering and material science. High levels of UV radiation and thermal loading can cause the premature degradation of polymers, coatings, and electronic components.

In the Algerian industrial sector, understanding the intensity of solar radiation is crucial for:

- Civil Engineering: Designing "bioclimatic" buildings that maximize natural lighting while minimizing heat gain to reduce air conditioning costs.
- Infrastructure Longevity: Selecting materials that can withstand the intense solar radiation of the High Plateaus and the Sahara without cracking or losing structural integrity.
- Agriculture: Optimizing greenhouse designs and irrigation schedules based on local solar intensity to maximize crop yields [3].

1.9. Applications of Solar Radiation

The ability to harness solar radiation has revolutionized modern engineering, offering a clean and inexhaustible alternative to fossil fuels.

In Algeria, the diversity of solar applications is not just a scientific interest but a key component of the national "Green Energy" roadmap.

These applications are generally classified based on how the solar energy is converted: directly into electricity (Photovoltaics) or into thermal energy (Solar Thermal) [3].

1.9.1. Photovoltaic (PV) Energy Conversion

Photovoltaic technology is the most common application of solar radiation. It relies on the "Photoelectric Effect," where semi-conductor materials (usually silicon) convert photons directly into a flow of electrons (DC electricity).

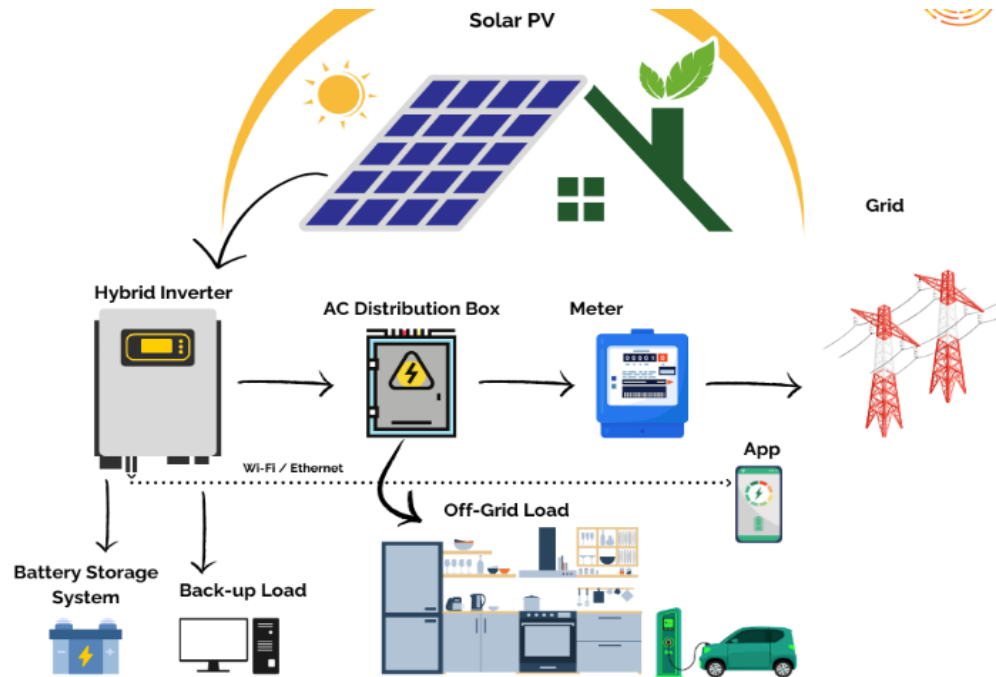


Figure 1.6 Explanation of Photovoltaic Work [16]

- **System Types:** PV systems can be "Grid-Tied," feeding electricity directly into the national Sonelgaz network, or "Stand-Alone" (Off-grid), which are essential for powering remote telecommunication towers or Saharan villages.
- **Technological Evolution:** Modern applications include "Tracking Systems" that move the panels to follow the sun's path, ensuring the maximum amount of Direct Radiation is captured throughout the day.
- **Algerian Impact:** Algeria has established several large-scale PV plants, such as those in the Adrar and Ghardaia clusters, which take advantage of the high global horizontal irradiance (GHI) levels in these regions [2].

1.9.2. Solar Thermal Systems (Low and Medium Temperature)

Solar thermal applications use the sun's energy to generate heat rather than electricity. This heat can be used for domestic, agricultural, or industrial purposes.

- a) Domestic Water Heating (CES - Chauffe-Eau Solaire): This is the most widespread thermal application. Solar collectors absorb radiation to heat a fluid that transfers its thermal energy to a water tank. In Northern Algeria, this technology significantly reduces household gas consumption during the winter months.
- b) Solar Cooking and Drying: In agricultural sectors, solar radiation is used to dry crops (like dates in Biskra) in controlled environments, preventing spoilage and improving product quality.
- c) Solar Pumping: One of the most vital applications for Algerian Saharan agriculture is the use of solar energy to power pumps that extract groundwater. This eliminates the need for expensive diesel generators and long-distance fuel transport.

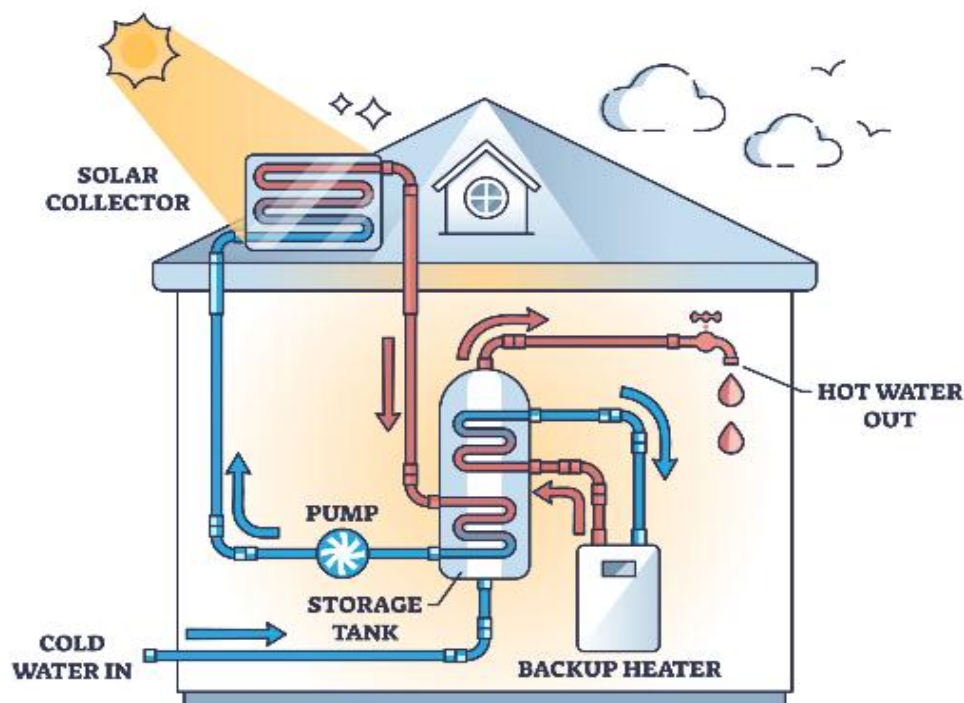


Figure 1.7 Solar Water Heating [3]

1.9.3. Concentrated Solar Power (CSP)

Concentrated Solar Power (CSP) systems are utility-scale applications that use mirrors or lenses to focus a large area of Direct Normal Irradiance (DNI) onto a small receiver. The intense heat generated is used to drive a steam turbine, which produces electricity.

- **Parabolic Troughs:** The most mature CSP technology. Algeria's Hassi R'mel Integrated Solar Combined Cycle (ISCC) plant was one of the first of its kind, combining natural gas with a parabolic trough field.
- **Solar Towers:** These use a field of tracking mirrors (heliostats) to focus light onto a receiver at the top of a central tower, achieving extremely high temperatures for high-efficiency power cycles.

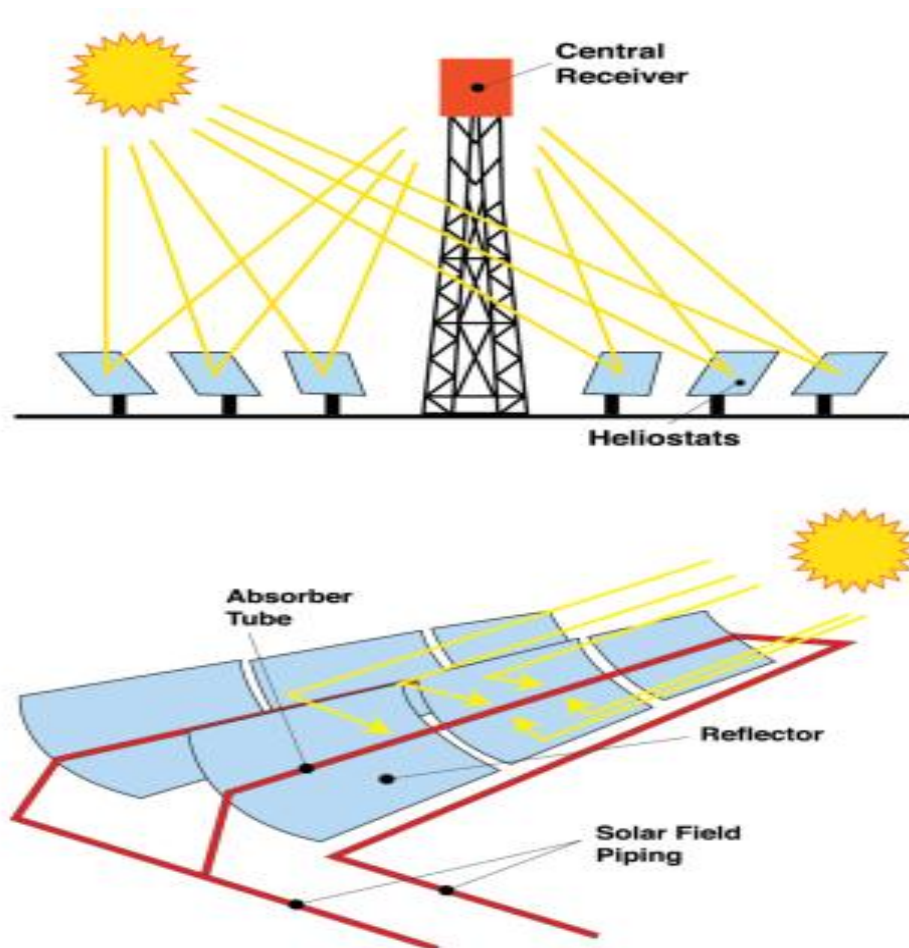


Figure 1.8 concentrated solar power types [3]

1.9.4. Solar Desalination

As a country facing water stress, Algeria is increasingly looking toward solar-powered desalination. This application uses solar energy to remove salt from seawater or brackish groundwater.

- Direct Distillation: Using solar stills to evaporate water and collect the pure condensate.
- Indirect Systems: Using PV or CSP to provide the electricity needed for Reverse Osmosis (RO) membranes. This is a strategic application for providing drinking water to coastal cities and remote Saharan outposts without increasing the nation's carbon footprint [5].

1.9.5. Space and Satellite Applications

Beyond the Earth's atmosphere, solar radiation is the primary power source for almost all satellites and space exploration missions. Because the solar intensity is higher in space (AM 0), solar arrays can be smaller and more efficient than those used on the ground. These arrays must be designed to withstand extreme temperature shifts and high UV exposure [4].

1.9.6. Bioclimatic Architecture and Passive Solar Design

In the construction sector, solar radiation is used "passively" without mechanical systems. This involves designing buildings with specific orientations, window sizes, and thermal mass to capture solar heat in the winter and reject it in the summer.

In Algeria, traditional architecture in the M'zab Valley is a historical example of bioclimatic design, utilizing solar angles to maintain comfortable indoor temperatures naturally. Modern Algerian engineering is now re-integrating these concepts into urban planning to reduce the energy demand of modern cities [6].

1.10. Conclusion

Chapter 1 has established the theoretical and physical foundation necessary to understand solar radiation as a primary energy resource. For Algeria, mastering this resource is a strategic priority, supporting the national goal of achieving 15,000 MW of renewable capacity by 2035.

The core findings of this chapter can be summarized as follows:

- **Terminology:** A fundamental distinction was made between Solar Irradiance (instantaneous power in W/m^2) and Solar Irradiation (cumulative energy over time in Wh/m^2). This distinction is critical for both the technical sizing and economic evaluation of solar projects.
- **Atmospheric Physics:** We analyzed how the Solar Constant ($1361 \text{ W}/\text{m}^2$) is attenuated by the atmosphere through absorption and scattering. In the Algerian context, Saharan Dust was identified as a major factor that increases diffuse radiation while reducing the direct beam, directly influencing the choice between PV and CSP technologies.
- **Applications:** The chapter reviewed the versatile applications of solar energy, from direct electricity generation (PV) and concentrated thermal power (CSP) to desalination and bioclimatic architecture.

Ultimately, while theoretical models provide a baseline, the inherent variability of the Saharan climate requires high-precision, real-time data. To transition from theory to practical implementation, we must utilize specialized tools to monitor the resource.

Chapter 2

Instruments and Techniques

for Solar Irradiance

Measurement

2.1. Introduction

The successful implementation of solar energy projects depends entirely on the availability of high-quality, site-specific data. While Chapter 1 provided the theoretical framework for understanding solar physics, Chapter 2 focuses on the technical transition from theory to practice. Measuring solar irradiance is a complex task because the sensor must be able to accurately capture energy across the entire solar spectrum, often under extreme environmental conditions like the heat and dust of the Algerian Sahara [1].

For a researcher or engineer, the choice of measurement strategy is a balance between required precision and available budget. This chapter explores the landscape of modern measurement, ranging from high-cost international standards to innovative, low-cost custom solutions designed for local implementation.

2.2. Solar Measurement Strategies

Measuring solar radiation can be approached through several different strategies depending on the application (e.g., small-scale PV monitoring versus utility-scale power plant forecasting). These strategies are broadly categorized based on the "Path" taken to acquire the data: the Professional/Standard path and the Custom/Development path.

2.2.1. Categorization of Measurement Methods

- a. **Standardized Measurement:** This strategy relies on "Off-the-shelf" professional instruments that are pre-calibrated and certified by international meteorological organizations. These devices use sophisticated physical principles to ensure that the measurement remains linear regardless of temperature or the angle of the sun.
- b. **Custom Sensing and Prototyping:** This strategy involves building a measurement system using individual electronic components and microcontrollers (like Arduino). It is a highly educational and cost-effective approach, allowing for the integration of multiple sensors to monitor specific local variables such as dust accumulation or temperature impacts.
- c. **Satellite-Derived Modeling:** Rather than using ground-based hardware, this strategy uses satellite imagery and atmospheric models to estimate irradiance. While useful for large-scale maps, it often lacks the precision required for real-time site monitoring in areas with high aerosol (dust) activity [2].

2.2.2. Key Functional Requirements for a Measurement System

Regardless of the strategy chosen, every measurement system must address three fundamental challenges:

- **Spectral Sensitivity:** The sensor must be sensitive to the wavelengths where the most solar energy is concentrated (approx. 300 nm to 2500 nm).
- **Linearity:** The output signal of the sensor (Voltage or Current) must increase linearly with the increase in solar intensity.

- Response Time: The system must be fast enough to capture rapid changes in irradiance caused by moving clouds or dust storms.

2.2.3. The Choice for Local Design

In the context of this thesis, the primary objective is to investigate methods that do not require the massive financial investment of professional pyranometers. By focusing on "Custom Sensing," we explore how affordable components—specifically photodiodes, digital sensors, and mini-solar panels—can be calibrated to provide reliable data for local energy projects [3].

2.3. Standard Meteorological Instrumentation (The Professional Path)

In the industrial and scientific community, solar measurement is governed by strict international standards to ensure that data collected in different parts of the world can be compared accurately. These instruments are designed to have high "flatness" in their spectral response, meaning they treat all wavelengths of solar energy equally. The most recognized standards for these devices are defined by ISO 9060 and the World Meteorological Organization (WMO) [1].

2.3.1. The Pyranometer

The pyranometer is the primary instrument used to measure Global Horizontal Irradiance (GHI). It is designed to measure the solar radiation flux density from a hemispherical field of view (180 degrees) on a flat surface.

There are two main physical technologies used in professional pyranometers:

- a. Thermopile Pyranometers: These are the "Gold Standard" in meteorology. They consist of a black-coated surface that absorbs solar radiation, causing a temperature increase. This heat is converted into a small voltage by a series of thermocouples (a thermopile). Because they rely on heat, they are sensitive to the entire solar spectrum (300 nm to 2800 nm).

- b. Photodiode-Based Pyranometers: These use a silicon semiconductor sensor. While they are faster and cheaper than thermopile versions, their spectral response is limited (usually 400 nm to 1100 nm). They are often used for monitoring the performance of photovoltaic plants because their response matches the response of PV panels [1].

Measurement of Diffuse Radiation: To measure Diffuse Horizontal Irradiance (DHI) specifically, a pyranometer is equipped with a "Shadow Ring" or a "Shading Disk" that moves to block the direct beam of the sun. By subtracting the diffuse value from the global value, engineers can calculate the direct component mathematically [4].



Figure 2. 1 pyranometer [5]



Figure 2.2 The Pyrheliometer [5]

2.3.2. The Pyrheliometer

While a pyranometer "sees" the whole sky, a Pyrheliometer is a highly specialized instrument designed to measure only Direct Normal Irradiance (DNI)

- **Design:** It consists of a long, narrow tube (collimator) that limits the field of view to a very small angle (typically 5 degrees) centered on the sun's disk.
- **Tracking Requirement:** Unlike the pyranometer, which is fixed horizontally, a pyrheliometer must be mounted on an automated Solar Tracker. This tracker follows the sun's position in the sky with high precision throughout the day to ensure the sensor is always perpendicular to the sun's rays.

In Algeria, DNI data is critical for the development of Concentrated Solar Power (CSP) projects in the Sahara. Errors in DNI measurement can lead to massive financial losses in these large-scale infrastructures [5].

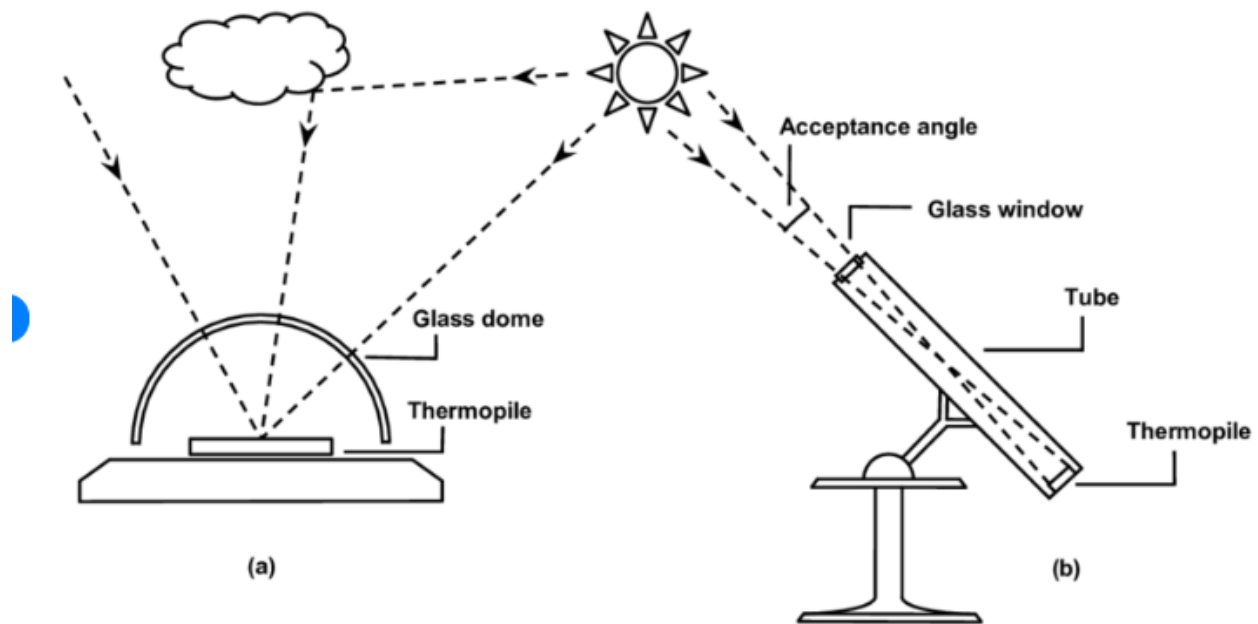


Figure 2.3A schematic illustration of a pyranometer (a) and a pyrheliometer (b) [5]

2.3.3. Advantages and Constraints of Professional Instruments

The professional path offers the highest level of data integrity, but it comes with significant challenges for independent researchers and students.

Advantages:

- **Traceability:** Instruments are calibrated against the "World Radiometric Reference" in Davos, Switzerland.
- **Durability:** Designed to operate for decades in harsh outdoor environments.
- **Accuracy:** Measurement errors are typically less than 2% for high-quality (Class A) sensors.

Constraints:

- **Extreme Cost:** A single high-end pyranometer can cost between 2,000 and 5,000 USD (480,000 to 1,200,000 Algerian Dinars), while a full station with a tracker and pyrheliometer can exceed 20,000 USD (4,800,000 Algerian Dinars).

- Maintenance: Sensors require daily cleaning, especially in the Algerian Sahara, where dust accumulation (soiling) on the glass domes can introduce errors of 10% to 20% in just a few days [3].
- Complexity: They require specialized data loggers and stable power supplies, making them difficult to deploy in remote, unmanaged locations.

Tableau 2.1 Comparison of Pyranometers vs. Pyrhemimeters

Feature	Pyranometer	Pyrhemimeter
Primary Measurement	Global Horizontal Irradiance (GHI)	Direct Normal Irradiance (DNI)
Field of View	180 degrees (Hemispherical)	~5 degrees (Collimated)
Mounting	Fixed (Horizontal)	Active Tracking Required
Main Use	PV System Monitoring	CSP Plant Performance
Standard	ISO 9060	WMO Standard

2.3.4. Calibration and Traceability of Professional Sensors

Calibration is the process of comparing a measurement instrument against a known reference standard to determine its accuracy and establish its sensitivity constant. For solar radiation sensors, this process is governed by strict international protocols to ensure Traceability[6].

1. The Radiometric Hierarchy

A measurement is only as good as its "Traceability Chain." In solar science, every professional pyranometer in the world is eventually traced back to a single reference:

- The World Radiometric Reference (WRR): Maintained at the World Radiation Centre (PMOD/WRC) in Davos, Switzerland. This is the absolute "Gold Standard."
- Secondary Standards: National meteorological centers (like the CDER in Algeria or the ONM) maintain secondary standard instruments that are periodically sent to Davos for comparison.
- Field Sensors: The pyranometers used in the field are then calibrated against these secondary standards.

2. Calibration Methodologies (ISO 9847)

- a. Outdoor Calibration (Side-by-Side): This is the most common method. The sensor to be calibrated (Test Sensor) is placed on a horizontal platform next to a "Master Reference" sensor. Data is recorded over several clear sky days. The Sensitivity (S) is then calculated as the ratio of the electrical output (mV) to the irradiance measured by the master (W/m^2).
- b. Indoor Calibration: Performed using a Solar Simulator. This artificial light source mimics the solar spectrum using xenon lamps. While fast, it requires complex corrections to account for the difference between artificial light and real sunlight.

2.3.5. Sources of Measurement Errors and Uncertainties

To provide a high-quality scientific analysis, we must acknowledge that no measurement is 100% perfect. Understanding the sources of error allows us to interpret the data from our custom system more accurately, especially in the extreme climate of the Algerian Sahara.

1. The Cosine Error (Directional Response)

Ideally, a pyranometer's response should follow the "Cosine Law." This means that if the sun is at an angle, the sensor should only capture the vertical component of the light.

- The Problem: At low sun angles (sunrise and sunset), the glass dome of the sensor can reflect light rather than letting it pass through to the sensing element.
- Impact: This often leads to an underestimation of irradiance during the early morning and late evening.

2. Temperature Dependency (Thermal Drift)

Silicon sensors and thermopiles are both sensitive to temperature changes.

- Mechanism: As the temperature of the sensor body increases, its internal resistance and electron mobility change.
- Saharan Context: In regions like Adrar or In Salah, where ambient temperatures can reach 50 degrees Celsius and sensor surfaces can reach 70 degrees Celsius, this "Thermal Drift" can introduce an error of 2% to 5% if a compensation circuit is not used.

3. Spectral Mismatch Error

Different sensors "see" different colors of light.

- The Error: A thermopile pyranometer is "black" and absorbs everything (300 nm to 2800 nm). However, our BPW34 or Mini-Solar Panel sensors are mostly sensitive to the visible and near-infrared range (400 nm to 1100 nm).
- Result: If the atmosphere changes (due to humidity or dust), the color of the sky shifts, and our silicon sensors might under-read or over-read compared to a professional thermopile.

4. The Soiling Factor (Dust and Sand)

This is the most significant source of error for solar installations in Algeria.

- Mechanism: Airborne Saharan dust and sand settle on the transparent cover of the sensor.
- Data Impact: Studies at the CDER have shown that uncleaned sensors can lose 1% of their accuracy per day during high-dust seasons. If a sensor is left uncleaned for a month, the error can exceed 25% [10].

2.4. Low-Cost Design Architectures (The Custom Path)

In academic research and local industrial applications, the high cost of professional sensors often necessitates the development of custom-built measurement systems. These "Low-Cost" architectures leverage mass-produced semiconductor components to replicate the functions of professional pyranometers at a fraction of the cost. In the Algerian context, these systems are particularly valuable for decentralized monitoring in remote Saharan regions where expensive equipment may be difficult to maintain or replace [6][2].

This section provides a detailed technical breakdown of the three hardware methodologies selected for this study.

2.4.1. Method A: Digital Integrated Sensing (BH1750)

Method B shifts from a component-level analog design to an integrated digital solution. The BH1750 is a sophisticated digital ambient light sensor that simplifies the measurement process by performing the amplification and conversion internally.

- Operating Principle: The BH1750 contains an integrated photodiode whose signal is processed by an internal 16-bit Analog-to-Digital Converter (ADC). Unlike the analog method, which outputs a raw voltage, the BH1750 outputs a digital value directly in Lux (illuminance).
- Communication and Resolution: The sensor utilizes the I²C (Inter-Integrated Circuit) protocol, allowing for high-speed data transfer with only two signal wires (SDA and SCL). It features a "High-Resolution Mode" that allows it to detect very

small changes in light intensity, which is useful for monitoring low-light conditions or early-morning irradiance [3].

- **Mathematical Calibration:** Since the sensor outputs Lux (human-perceived brightness), a calibration factor is applied within the Arduino code to convert the digital Lux value into Irradiance (W/m^2). A common approximation used in solar research is $1 \text{ W}/\text{m}^2 \approx 126.7 \text{ Lux}$ for natural sunlight, though this is further refined through ground-level testing.

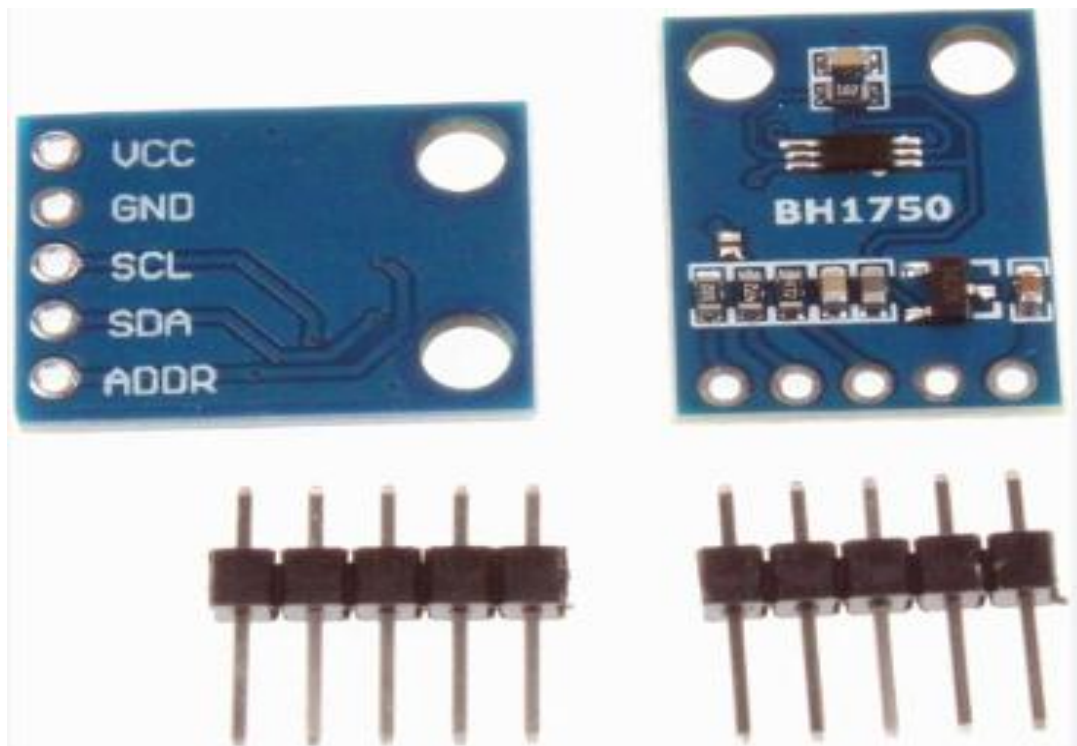


Figure 2.4 NOYITO BH1750 Digital Light Intensity Sensor [14]

Technical Specifications of Method A:

- Sensing Chip: BH1750FVI.
- Data Interface: I²C (Address 0x23 or 0x5C).
- Range: 1 to 65,535 Lux.

- Main Advantage: High immunity to electrical noise and pre-calibrated internal processing.

2.4.2. Method B: Analog Photodiode Sensing (BPW34)

This method represents the fundamental electronic approach to light measurement, utilizing the physics of the silicon PN junction. The BPW34 is a high-speed silicon PIN photodiode with a large radiant-sensitive area, making it ideal for capturing solar flux.

- Operating Principle: When photons strike the active area of the BPW34, they generate electron-hole pairs, resulting in a photocurrent (I_p). In this design, the photodiode is operated in Photovoltaic Mode (zero-bias), which ensures the highest degree of linearity between the incident light and the resulting current.
- The Transimpedance Amplifier (TIA): Because the photocurrent produced by solar radiation is extremely weak (typically in the range of micro-Amperes), it cannot be accurately sampled by the Analog-to-Digital Converter (ADC) of a microcontroller. To resolve this, an Operational Amplifier (Op-Amp)—specifically the LM358—is configured as a Transimpedance Amplifier.
- Signal Conversion Logic: The Op-Amp takes the current from the photodiode and converts it into a voltage (V_{out}) according to the feedback resistor (R_f). A 100k Ohm resistor is selected here to provide a balance between sensitivity and dynamic range, ensuring the output voltage remains within the 0V–5V range required by the Arduino.

Technical Specifications of Method B:

- Sensor: BPW34 (Silicon PIN Photodiode).
- Amplification Stage: LM358 (Dual Operational Amplifier).
- Signal Output: Analog Voltage (0V to 5V).
- Complexity: Requires careful circuit shielding to avoid electromagnetic interference (noise).

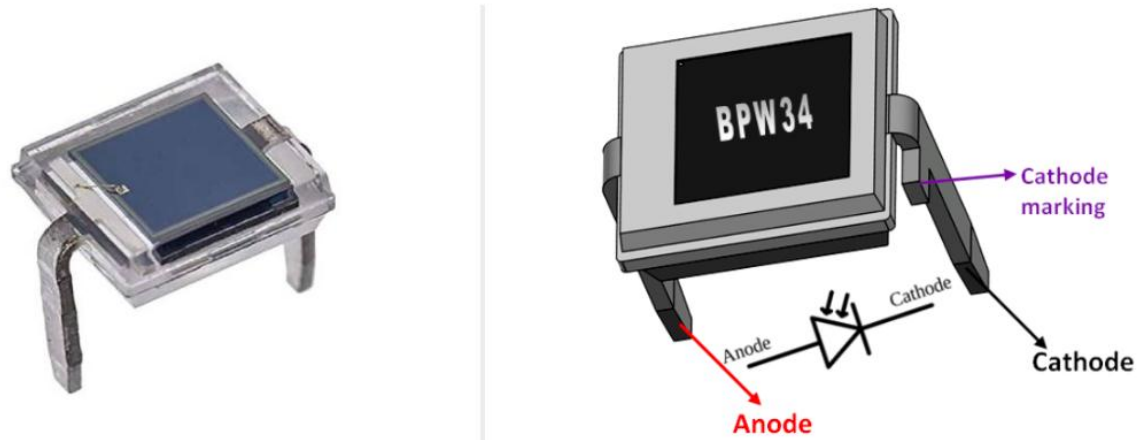


Figure 2.5 BPW34 Photodiode And Pinout [13]

2.4.3. Method C: Mini-PV Characterization (Solar Panel as Sensor)

This method is based on the principle that a photovoltaic panel can act as its own sensor. This is the most "system-accurate" method because the sensor behaves exactly like the large-scale PV arrays it is meant to monitor.

- **Operating Principle:** In silicon solar cells, the Short-Circuit Current (I_{sc}) is almost perfectly proportional to the intensity of incident light. Unlike the Open-Circuit Voltage (V_{oc}), which plateaus very quickly even in low light, the current increases linearly from sunrise to solar noon.
- **Current Measurement:** To safely measure the current generated by the 5V / 200mA Mini Solar Panel, an ACS712 current sensor is integrated into the circuit. The ACS712 uses the Hall Effect to measure the current flowing through the circuit without direct electrical contact, outputting an analog voltage that the Arduino can interpret.
- **Strategic Application:** This method is particularly relevant for the Algerian Saharan environment. By using the panel as a sensor, researchers can also monitor the impact of soiling (dust accumulation). As dust settles on the panel, the measured current drops, providing a direct measurement of "Soiling Losses," which is a major concern for the Algerian energy transition [5].

Technical Specifications of Method C:

- Primary Sensor: Polycrystalline Mini Solar Panel (5V / 200mA).
- Transducer: ACS712-05B Current Sensor (Hall Effect).
- Measured Parameter: Short-Circuit Current (Isc).
- Main Advantage: Direct correlation to PV power production and high durability in outdoor desert conditions.

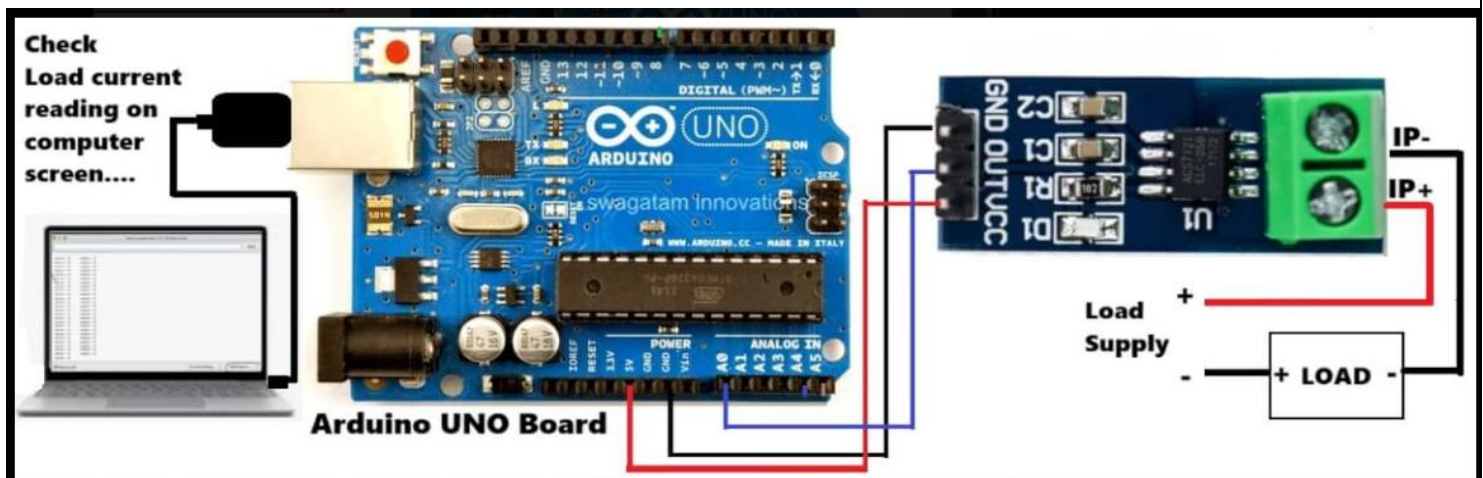


Figure 2.6 Wiring diagram showing the voltage sensor module connected to Arduino UNO [18]

2.4.4. Data Acquisition and Processing System (DAQ)

A sensor alone is useless without a system to capture and process its signal. This section details the Data Acquisition (DAQ) logic used in our custom system.

1. Analog-to-Digital Conversion (ADC) Math

The Arduino Nano/Uno uses a 10-bit ADC to translate the voltage from our sensors into a digital number that the computer can understand.

- Resolution Calculation: The ADC divides the 5V reference into 1024 discrete steps (2 to the power of 10).
- Step Size: $5V / 1024 = 4.88$ milli-Volts (mV) per step.

- This means our system can detect changes as small as 0.0048V. In terms of irradiance, this typically corresponds to a resolution of approximately 5 to 10 W/m^2 .

2. Sampling Rate and Signal Averaging

Solar radiation can fluctuate rapidly due to moving clouds. To get a "stable" reading, we implement a two-stage processing logic in our code:

1. Sampling: The Arduino takes a reading every 100 milliseconds.
2. Averaging: It calculates the average of 600 readings to produce a 1-minute average. This filtering technique is essential to remove "noise" from the electronic circuit and to provide a smooth data curve for our thesis results.

3. Data Storage and Visualization

Our system provides two methods for data handling:

- Serial Monitoring: Real-time data is sent to a PC via USB for immediate graphing.
- SD Card Integration: For remote sites in the desert, an SD Card Module is used to save the time-stamped data in a .CSV format, which can be easily opened in Excel or MATLAB for final analysis.

4. Comparative Analysis of Measurement Methods

Choosing the right measurement method requires a careful evaluation of the trade-offs between precision, technical complexity, and economic feasibility. In the context of this thesis, we evaluate the three custom-designed methods—Analog Photodiode (BPW34), Digital Sensing (BH1750), and Mini Solar Panel (Self-Sensing)—against the industrial standard (Pyranometer).

Tableau 2.2 Comparative Matrix of Solar Measurement Techniques

Criteria	Standard Pyranometer	Method A: BPW34	Method B: BH1750	Method C: Mini-Panel
Accuracy	Very High (< 2%)	Medium (Linear)	High (Pre-calibrated)	High (PV-Specific)
Spectral Range	300 - 2800 nm	400 - 1100 nm	400 - 700 nm	400 - 1100 nm
Output Type	Analog (Low mV)	Analog (Voltage)	Digital (I ² C)	Analog (Current)
Calibration	Factory Certified	Manual (Required)	Built-in (Lux)	Manual (Required)
Ease of Use	Plug-and-Play	Complex (Circuit)	Simple (I ² C)	Medium (Load)

2.4.5. Discussion and Justification of Choice

Standard Instruments: While they remain the ultimate reference, their extreme cost makes them inaccessible for widespread decentralized monitoring in Algeria.

- Method A (BH1750): The digital nature makes it incredibly easy to interface with microcontrollers. However, because it is designed for "Ambient Light" (Lux), its spectral sensitivity is mostly in the visible range, potentially ignoring the significant infrared energy available in the Saharan regions.

Final Selection for Practical Implementation: For the experimental phase of this work

- Method B (BPW34): This is excellent for high-speed response but requires a stable amplification circuit. It is prone to signal noise and thermal drift, which can be problematic in the high temperatures of the Algerian desert.
- Method C (Mini Solar Panel) has been selected as the primary measurement tool. The justification for this choice is based on three main factors:
 1. Technological Consistency: Since the goal is to monitor solar energy for power production, using a PV panel as a sensor ensures that the measurement accounts for the same spectral losses and temperature coefficients as a full-scale solar farm.
 2. Durability: The glass and polymer encapsulation of a mini solar panel is much more resistant to Saharan sand erosion and high UV exposure compared to exposed plastic photodiodes or small digital chips.
 3. Direct Correlation: The output (Current) directly represents the "Short-Circuit Current," which is the most reliable indicator of irradiance in the PV industry [5] [2].

2.5. Detailed Study of Components (Technical Data Sheets)

this section provides the technical specifications and physical principles of the individual electronic components that make up the custom measurement systems.

2.5.1. Silicon PIN Photodiode (BPW34)

The BPW34 is a semiconductor device that converts light into electrical current through the photoelectric effect at its PN junction.

- Operating Voltage: Up to 32V (Reverse bias) or 0V (Photovoltaic mode).
- Spectral Sensitivity: 430 nm to 1100 nm (Peak at 950 nm).
- Radiant Sensitive Area: 7.5 mm².
- Short Circuit Current: Approx. 47 micro-Amps (at 1000 Lux).
- Datasheet Significance: The large sensitive area allows it to capture enough photons even in slightly shaded conditions.

2.5.2. Digital Light Sensor (BH1750FVI)

This integrated circuit acts as a complete light-to-digital converter.

- Supply Voltage: 2.4V to 3.6V.
- Resolution: 16-bit (detects changes as small as 1 Lux).
- Communication: I²C Bus.
- Internal Functioning: It contains an integrated photodiode and an ADC (Analog to Digital Converter) that filters out 50Hz/60Hz light noise from artificial sources.

2.5.3. Operational Amplifier (LM358)

The LM358 is used in Method A to amplify the weak signal from the photodiode.

- Architecture: Dual Op-Amp (two amplifiers in one chip).
- Input Voltage Range: 3V to 32V.
- Key Function: In our design, it operates as a Transimpedance Amplifier, where it "forces" the photodiode current through a 100k Ohm resistor to create a readable

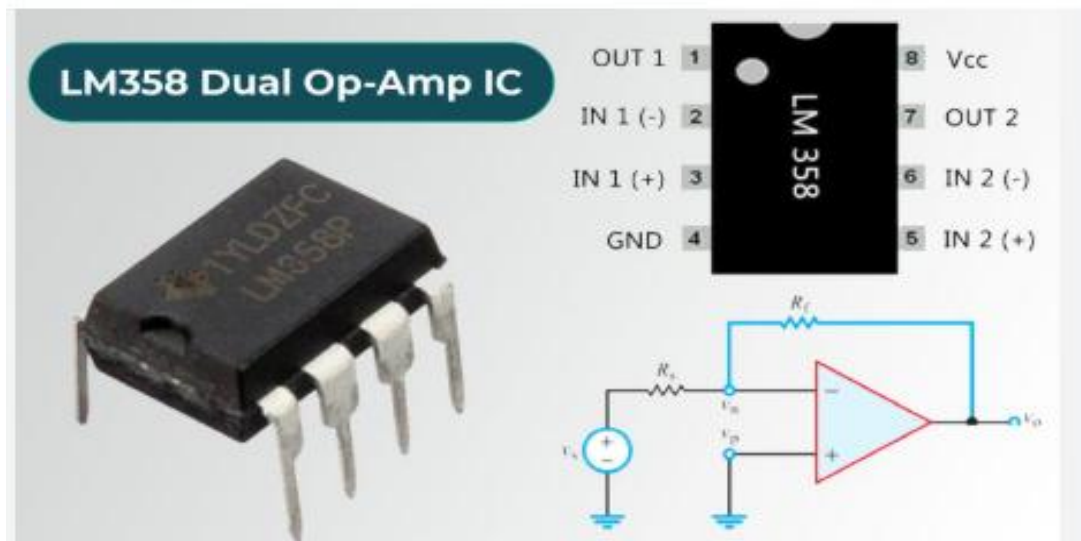


Figure 2.7 LM358 [19]

2.5.4. Voltage Sensor Module (5:1 Resistive Divider)

To safely monitor the open-circuit output voltage of the mini solar panel in Method C, a dedicated voltage sensor module is integrated into the data acquisition network. This electronic breakout board acts as a passive voltage attenuation stage, designed to scale voltages that exceed the microcontroller's safe input thresholds down to a readable range.

- **Operating Principle:** The module relies on a classic two-resistor voltage divider network to scale high analog inputs. It contains a series input resistor ($R1 = 4 \text{ k}\Omega$) and a shunt resistor tied to ground ($R2 = 1 \text{ k}\Omega$), creating a fixed 5:1 reduction ratio.
- **Maximum Input Voltage Range:** Capable of accepting DC voltage inputs from 0V up to 25V when paired with a standard 5V microcontroller ADC reference rail.
- **Signal Output:** Outputs a continuous, proportional analog voltage signal (0V to 5V) via the 'S' pin, matching the sampling limits of the Arduino analog interface.
- **Datasheet Significance:** This component eliminates the need for active signal-conditioning integrated circuits. It provides a highly stable, low-impedance input reference point that allows the firmware to mathematically reconstruct the absolute solar panel voltage curve without clipping or overheating.

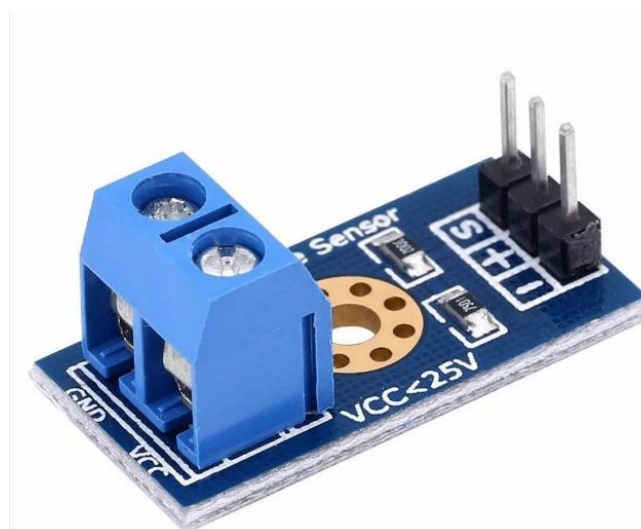


Figure 2.8 Voltage Sensor Module (5:1 Resistive Divider) [20]

2.5.5. Current Sensor (ACS712)

To measure the power output of the mini solar panel in Method C, the ACS712 module is employed.

- Measurement Principle: Hall Effect. It detects the magnetic field generated by current flowing through a copper conduction path.
- Sensitivity: 185 mV/A (for the 5A version).
- Isolation: 2.1 kVRMS voltage isolation between the panel and the Arduino, protecting the microcontroller from surges.

2.5.6. The Processing Core (Arduino Nano/Uno)

The Arduino acts as the "Brain" of the measurement system.

- Microcontroller: ATmega328P.
- ADC Resolution: 10-bit (reads voltages from 0V to 5V in steps of 4.9 mV).
- Operating Frequency: 16 MHz.
- Role: It samples the analog or digital signals from the sensors, applies the calibration formulas, and sends the data to a computer for logging.

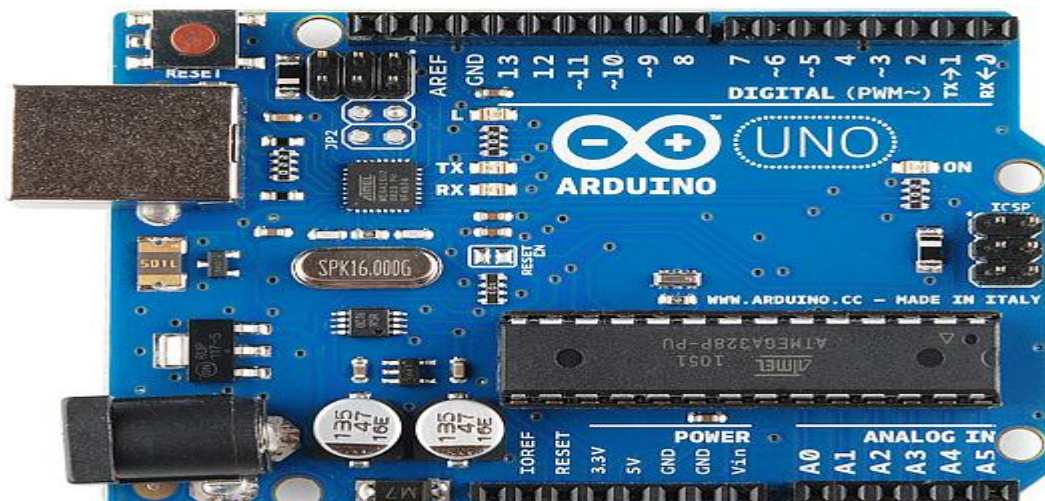


Figure 2.9 Arduino Uno [21]

2.6. Conclusion

Chapter 2 has detailed the transition from the theoretical study of solar physics to the practicalities of hardware instrumentation. We established that while professional instruments like Pyranometers and Pyrhemimeters are the global gold standard, their high cost and maintenance needs in the Algerian Sahara make custom, low-cost alternatives a strategic necessity for local research.

Three primary custom methodologies were analyzed:

- Method A (BH1750): A digital, noise-resistant solution for ambient light.
- Method B (Bpw34): An analog approach focusing on raw photocurrent.
- Method C (Mini-Panel): A "self-sensing" approach that mimics full-scale PV behavior.

Based on our analysis, Method C was selected for this study due to its superior durability and direct correlation with photovoltaic energy production [2]. This chapter also provided the necessary technical specifications for the individual components, including the Arduino Nano and Voltage sensor module, to satisfy academic requirements for hardware validation.

With the hardware architecture now finalized, the next phase of this work involves the physical construction and calibration of the system.

Chapter 3

Design, Implementation and Performance Evaluation of the Proposed Methods

3.1. Introduction

The validation of solar energy assessment frameworks relies on transitioning from theoretical models to field-level empirical verification. While atmospheric formulations provide generalized data, localized microclimatic variations, dust suspensions, and rapid thermal shifts require localized physical data acquisition. This chapter details the physical design, breadboard assembly, firmware programming, and diagnostic analysis of three low-cost, ground-level measurement frameworks developed to replicate standard meteorological station capabilities[11].

The core objective of this experimental work is to establish a robust, decentralized methodology using accessible consumer electronics to bypass the high cost barriers of industrial pyranometers. By deploying different sensing technologies, this study evaluates the distinct operational behaviors of three specific frameworks:

- Method A (Digital Integrated Platform): Utilizes a BH1750 (Figure 2.5) ambient light chip on a GY-302 breakout board to evaluate digital signal filtering and communication via the I²C serial bus.
- Method B (Analog Transimpedance Platform): Details a custom component-level circuit using a BPW34 (Figure 2.4) silicon PIN photodiode and an LM358 (Figure 2.7) operational amplifier to achieve manual gain control.
- Method C (Self-Sensing PV Panel Platform): Implements a reference-cell approach using a 6V mini polycrystalline solar panel and a step-down resistor voltage divider module (Figure 2.8) to maximize outdoor durability.

Together, these parallel hardware setups provide the empirical field data necessary to evaluate the accuracy, linear continuity, and hardware constraints of alternative solid-state sensors under real-world regional clim

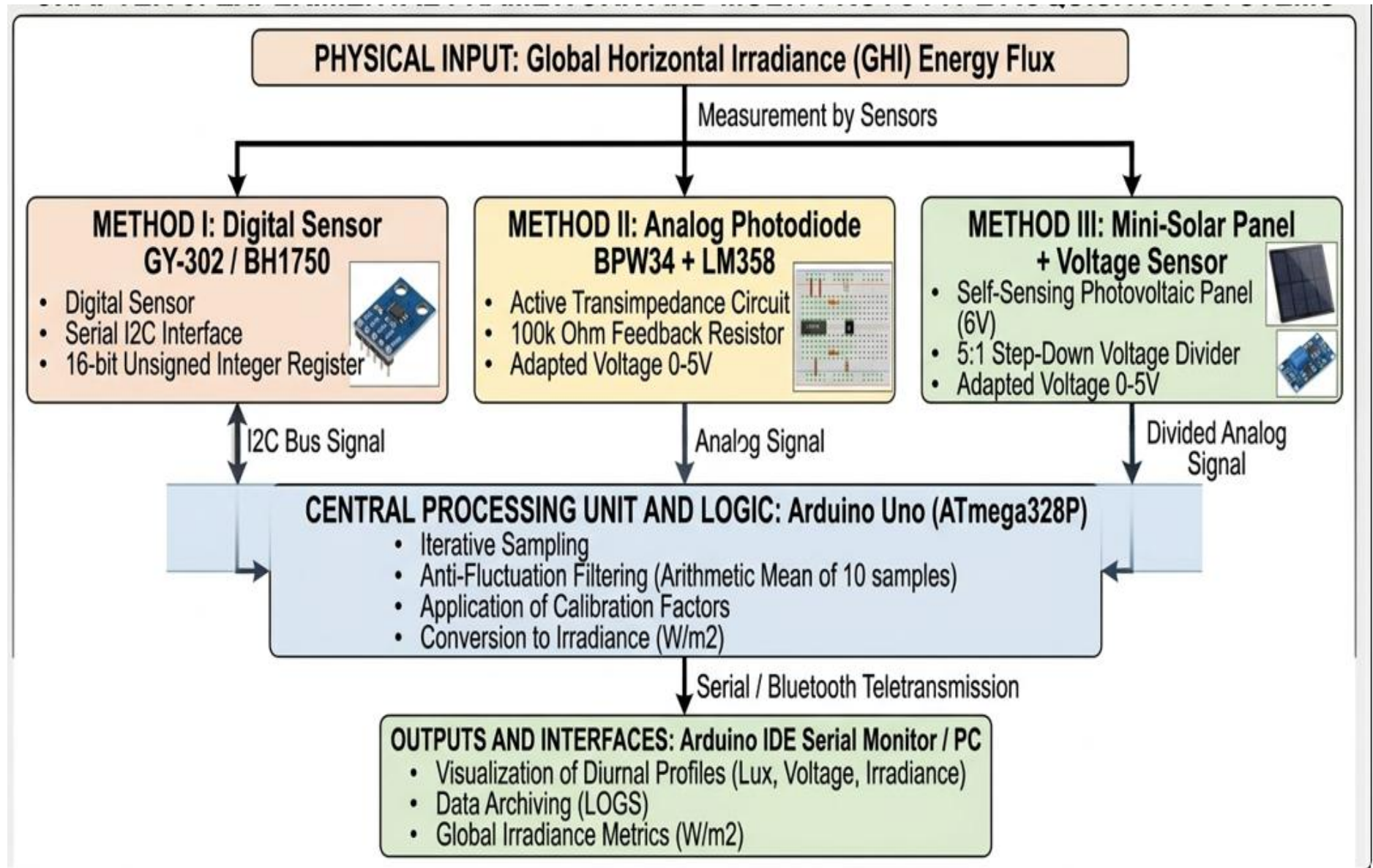


Figure 3.1 General synoptic Schema of the experimental methodology and solar data acquisition chains

3.2. Experimental Implementation of Method A: The Digital Integrated Platform (BH1750 / GY-302)

The first operational prototype developed, programmed, and field-tested within this research framework is the digital integrated ambient light sensing system. This configuration relies on a monolithic semiconductor layout where optical reception, signal amplification, noise filtering, and high-resolution analog-to-digital conversions are executed natively on a single silicon die. This architecture minimizes system exposure to common analog transmission problems such as electromagnetic interference, cable resistance voltage drops, and thermal noise variations.

3.2.1. Hardware Configuration and I²C Pin Mapping

The physical laboratory circuit was constructed by mounting a GY-302 breakout board module, which contains the BH1750FVI digital (Figure 2.5) ambient light chipset onto a high-density polymer breadboard array. This subsystem was electrically connected to an Arduino Uno (Figure 2.9) microprocessing development board driven by an ATmega328P microcontroller core[12]. Inter-device communication and power delivery are managed through a five-pin interface topology mapping directly to the controller's synchronous hardware infrastructure:

- Vcc (Power Input Connection): Wired directly to the stabilized V direct current (DC) power rail supplied by the onboard low-drop linear regulator of the Arduino Uno.
- GND (Common System Ground): Linked directly to the central reference ground plane of the microcontroller architecture to ensure an equivalent potential barrier across all circuit nodes.
- SDA(Serial Data Line): Interfaced directly with the hardware analog interface pin A4 of the Arduino Uno, establishing the bidirectional data highway for serial communication.

- SCL (Serial Clock Line): Linked directly to the hardware analog interface pin A5 of the Arduino Uno, carrying the clock synchronization square waves generated by the master controller.
- ADDR / ADD (Hardware Address Pin): Left completely disconnected and floating in the circuit layout[13].

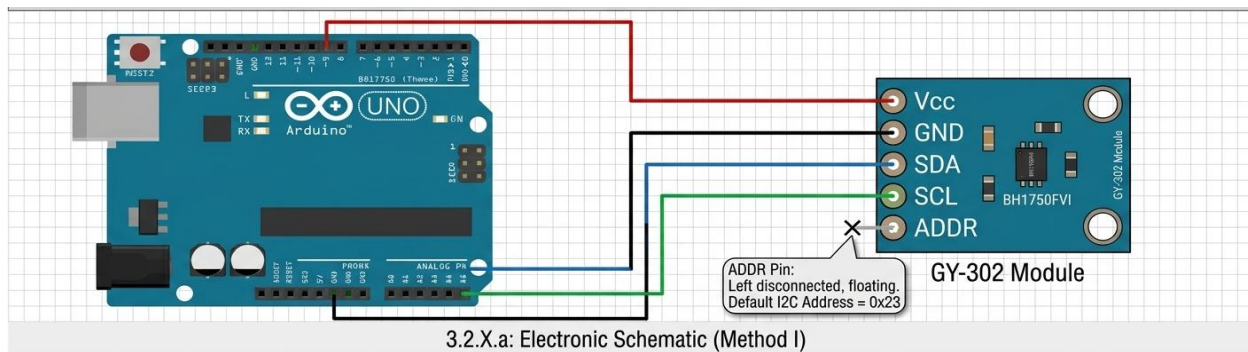
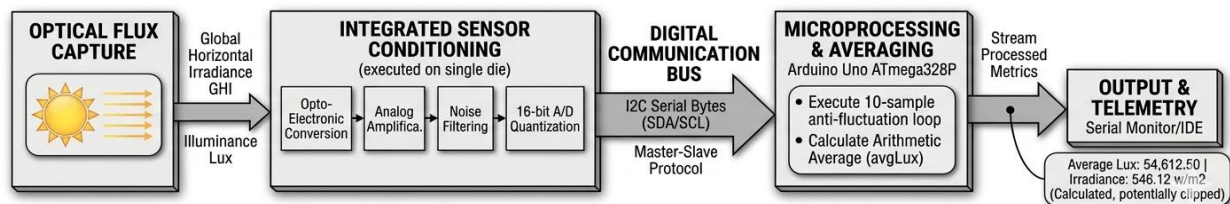
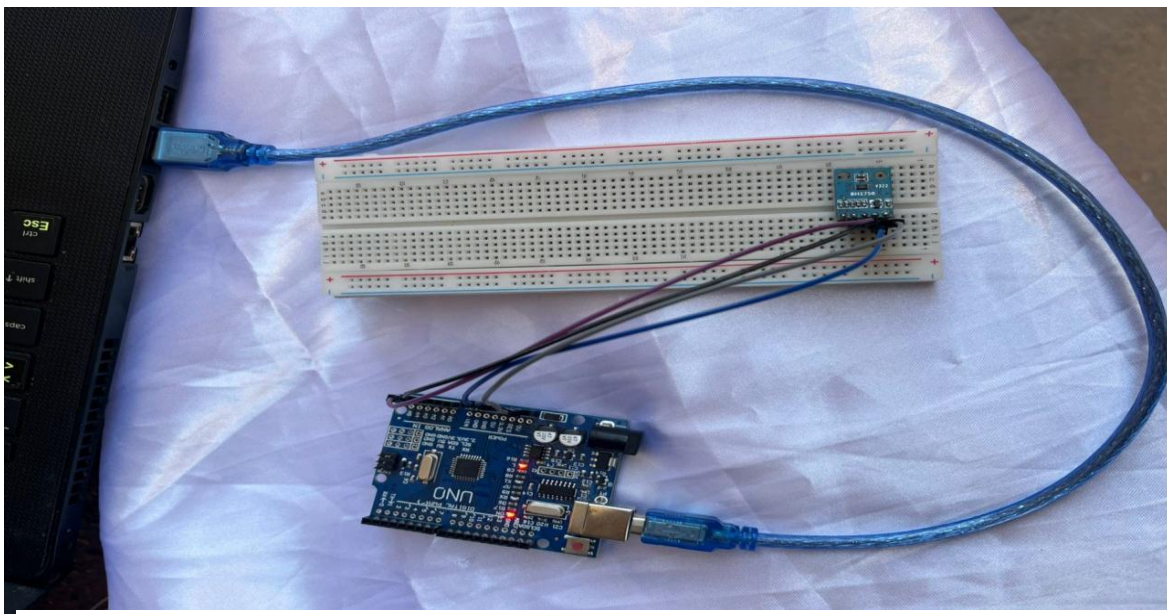


Figure 3.3 Physical prototype assembly and breadboard wiring layout of the unshielded digital BH1750 light sensor module interfaced with the Arduino Uno development core

The physical state of the ADDR pin determines the logical hexadecimal device identifier on the synchronous I²Cbus line. When this pin is tied to a high logical state Vcc, the internal logic gates shift the chip's listener address to (0 x 5C). By leaving this pin uncoupled, the sensor's internal pull-down resistor forces the pin to a low state, defaulting the breakout board to respond exclusively to the base hexadecimal slave address of 0 x 23. This layout ensures successful bus initialization and prevents transmission collisions during operational testing cycles.

3.2.2. Firmware Architecture and Digital Signal Filtering

To establish connection protocols, configure the registers of the BH1750FVI chip, and pull metrics over the I²Cserial lines, a firmware script was written, compiled, and uploaded using the Arduino IDE environment. The code structure relies on two main software dependencies: the low-level `<Wire.h>` library to manage the synchronization clock pulses and byte-transfer buffers of the microprocessing core, and the specialized `<BH1750.h>` library to decode raw lux registers. Before executing field measurements, it was necessary to download and import the proper BH1750 object library dependencies into the local development environment to activate device commands.

To suppress high-frequency electronic ripple, transient signal anomalies, and rapid minor fluctuations caused by localized dust particles or atmospheric turbulence, an anti-fluctuation averaging software filter was designed directly into the main loop execution block. Instead of recording raw instantaneous points, the system executes an iterative loop array that gathers 10 consecutive illuminance samples sequentially. A fixed timing delay of 200 ms(`delay(200)`) is executed between each loop iteration, providing an integration window for the chip's internal photodetection array to stabilize and preventing register collisions on the serial lines. Once the buffer loop finishes, the firmware calculates the precise arithmetic average value (`sumLux / 10.0`), producing a highly stable digital representation of current ambient illuminance before applying conversion scaling factors.

The final optimized source code implemented to drive the digital integrated testing platform is detailed below:

Line	Source Code Configuration
01	#include <Wire.h>
02	#include <BH1750.h>
03	
04	// Instantiate the digital light meter object reference
05	BH1750 lightMeter;
06	
07	void setup() {
08	// Initialize standard serial transmission at a baud rate of 9600 bps
09	Serial.begin(9600);
10	
11	// Initialize the low-level I2C wire bus communication protocol
12	Wire.begin();
13	
14	// Trigger initialization commands for the BH1750 digital sensor chipset
15	lightMeter.begin();
16	}
17	
18	void loop() {
19	float sumLux = 0;
20	
21	// Execute the 10-sample cumulative digital signal processing loop
22	for(int i = 0; i < 10; i++) {
23	float lux = lightMeter.readLightLevel(); // Fetch instantaneous illuminance metric
24	sumLux += lux; // Accumulate total sample values
25	delay(200); // Pacing delay interval for stability
26	}
27	
28	// Calculate the stabilized arithmetic average value of illuminance
29	float avgLux = sumLux / 10.0;

```

30 |
31 | // Mathematical conversion logic to derive solar Irradiance (W/m2)
32 | float irradiance = avgLux / 100.0;
33 |
34 | // Stream the processed hardware metrics out to the Serial Monitor
terminal
35 | Serial.print("Average Lux: ");
36 | Serial.print(avgLux);
37 | Serial.print(" | Irradiance: ");
38 | Serial.print(irradiance);
39 | Serial.println(" W/m2");
40 |
41 | // Pacing delay threshold before initializing the next data logging cycle
42 | delay(2000);
43 | }

```

3.2.3. Empirical Calibration Factor Optimization

A key phase of this experimental implementation involves the mathematical conversion of parsed optical illuminance, measured in Lux, into solar flux density metrics, represented as global horizontal irradiance in Watts per square meter (W/m²). In early software tests, the system computed solar irradiance values using a conservative conversion scaling factor:

$$\text{Irradiance (W/m}^2\text{)} = \frac{\text{avgLux}}{120.0}$$

When evaluating field test results against standard meteorological baselines, this divisor under-represented solar values during early clear sky operational phases. To correct this underestimation, the scaling algorithm was modified by shifting the code parameter to an optimized baseline denominator:

$$\text{Irradiance (W/m}^2\text{)} = \frac{\text{avgLux}}{100.0}$$

This modification provides a more accurate approximation of clear sky solar profiles during early morning tracking cycles, matching local regional climate data much more closely.

3.2.4. Meteorological Field Logging Data (May 22, 2026)

The primary prototype was deployed outdoors on May 22, 2026, to record an extended daily solar cycle. The device was aligned horizontally, and data was logged hourly from 07:00 through 19:00. Environmental logs for that testing date show a fast thermal escalation beginning at approximately 09:00, along with minor atmospheric cloud formations recorded during the 08:00 tracking window.

The empirical data collected during this test run is compiled in the table below:

Tableau 3.1 Hourly Climatic Metrics for Method A (May 22, 2026)

Logging Time Reference	Measured Average Illuminance (Lux)	Processed Solar Irradiance (W/ m^2)	Primary Field Observations and Notes
08:00	31,500.00	315.00	Partial localized cloud layers visible.
09:00	45,510.00	455.10	Clearing conditions; sudden temperature increase.
10:00	54,612.50	546.12	Sensor enters data saturation plateau.
11:00	54,612.50	546.12	Constant output; register clipping observed.
12:00	54,612.50	546.12	Solar Noon; output remains artificially flat.
13:00	54,612.50	546.12	Constant output; register clipping observed.

14:00	54,612.50	546.12	Constant output; register clipping observed.
15:00	53,802.50	539.02	Sensor exits the saturation boundary layer.
16:00	49,908.33	499.08	Normal evening decline profile.
17:00	39,300.83	393.01	Consistent low-light scaling response.
18:00	33,402.50	334.02	Late afternoon ambient declination curve.
19:00	15,057.50	150.58	Sunset phase; final baseline reading.

An evaluation of these field records shows that while the digital system performs reliably during morning and afternoon windows, it encounters a critical limitation at solar noon. The calculated irradiance values remain completely static at 546.12 W/m² between 10:00 and 14:00. This flatline indicates a hardware saturation boundary rather than a constant solar radiation profile, which will be analyzed mathematically later in this chapter.

3.3. Experimental Implementation of Method B: The Analog Transimpedance Photodiode Platform (BPW34 + LM358)

To address the hardware constraints observed during the field deployment of the digital chipset, a second custom circuit prototype was designed, assembled, and systematically evaluated. This architecture relies on an analog component-level approach using a silicon PIN photodiode combined with an active external signal-conditioning stage. By building an analog-driven acquisition framework, the system

provides full control over the electronic amplification factor, allowing the user to tune the detection sensitivity to prevent early clipping under peak sunlight.

3.3.1. Hardware Engineering and Circuit Assembly

The physical layout of this analog sensing platform uses a BPW34 (Figure 2. 10) silicon PIN photodiode as the primary light-to-current transducer. The photodiode is configured to operate in Zero-Bias Photovoltaic Mode. In this operational state, the external bias voltage is maintained at exactly 0V, which yields a linear relationship between the generated short-circuit photocurrent and the incoming solar flux density[14].

Because this raw photocurrent is extremely weak, typically ranging between small micro-amperes under natural ambient environments, it cannot be reliably processed by the standard analog-to-digital converter pins of a microcontroller without immediate signal corruption.

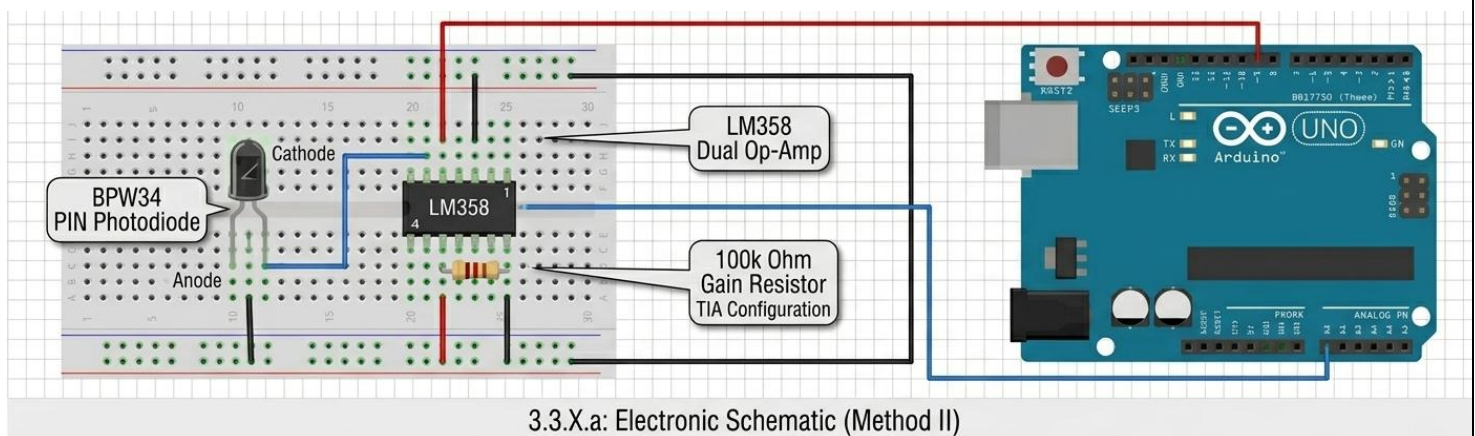
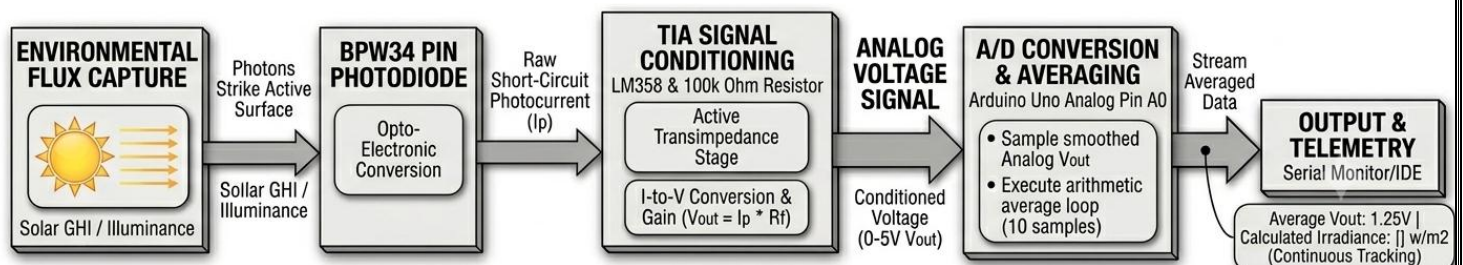


Figure 3.4 Synoptic Block Diagram (Method B)

To isolate and convert this weak current signal into a readable voltage level, an LM358 Dual Operational Amplifier integrated circuit was mounted on a high-density prototype breadboard to form a Transimpedance Amplifier (TIA) circuit structure. The electrical wiring interface of this multi-pin active device was routed according to a specific node mapping matrix:

- Pin 1 (Amplifier Output Line): Wired directly to Analog Input pin A0 of the Arduino Uno microcontroller board. This path delivers the boosted analog voltage signal to the internal converter core.
- Pin 2 (Inverting Input Node): Interfaced with the Cathode terminal of the BPW34 photodiode, while the Anode of the photodiode is tied to the common ground plane.
- Pin 3 (Non-Inverting Input Node): Tied directly to the central common ground line (GND) to establish a firm zero-voltage reference baseline for the amplifier stage.
- Pin 4 (Negative Power Rail): Connected directly to the circuit common ground terminal (GND) to facilitate single-supply operational characteristics.
- Pin 8 (Positive Power Rail): Connected directly to the stabilized plus 5V direct current power rail coming from the Arduino development board to power the internal transistor networks of the chip [15].

A high-precision feedback resistor with an electrical resistance rating of 100k Ohm was installed between Pin 1 and Pin 2 of the active operational amplifier chip. This electronic component forms the core feedback loop of the transimpedance configuration, defining the current-to-voltage conversion gain factor. Any raw photocurrent entering the inverting input is forced across this resistor network, generating a proportional output voltage that safely spans the 0V to 5V sampling window of the microprocessor core without overloading the semiconductor junctions.

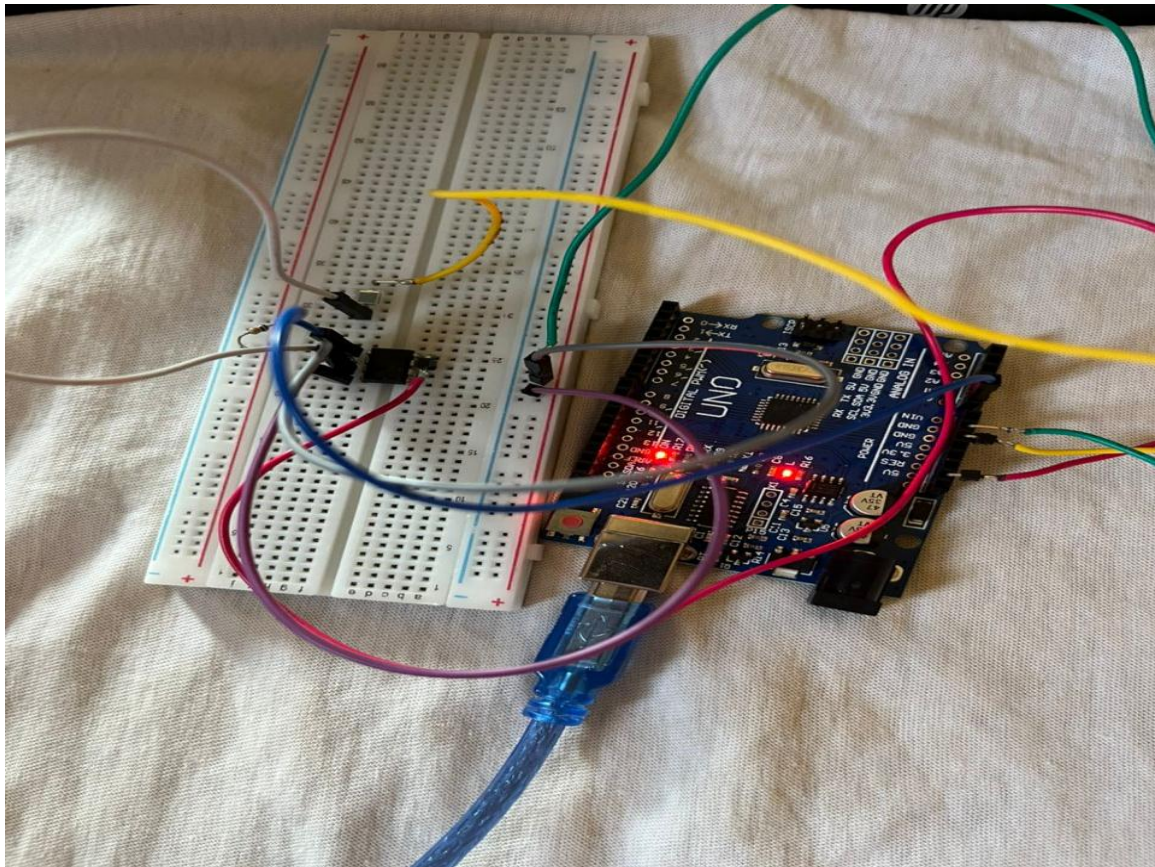


figure 3.5 Component-level breadboard implementation of the analog BPW34 PIN photodiode conditioned via an external active LM358 transimpedance operational amplifier circuit.

3.3.2. Analog Signal Quantization Firmware

To capture, filter, and display the amplified voltage curves coming from the transimpedance block, a target firmware routine was written and compiled inside the Arduino IDE. Unlike the digital I²C bus script used in the previous trial, this code interacts directly with the microcontroller's internal hardware register blocks via successive analog approximations. The internal Analog-to-Digital Converter (ADC) of

the ATmega328P processor samples the analog voltage waveform on Pin A0 and maps it into a 10-bit digital value space ranging from 0 to 1023 integer counts.

To ensure long-term data stability and suppress rapid high-frequency noise from the breadboard rails, an iterative accumulation loop filter was written into the firmware. The system captures 10 distinct sequential voltage measurements at a structured execution rate of 10 milliseconds between internal loop steps. Once the buffer loop finishes, the total accumulated integer values are divided by 10.0 to generate a smoothed analog reference number. This filtered integer count is then scaled using a linear voltage step multiplier of 4.88 mV per count, which is derived from dividing the 5.0V source voltage by the 1023 total quantization steps of the 10-bit converter module.

The exact embedded C source code implemented to drive this analog transimpedance verification circuit is structured as follows:

Line	Source Code Configuration
01	// Explicit definition of the analog measurement interface pin
02	const int sensorPin = A0;
03	
04	// Experimentally calibrated reference voltage factor for peak scale alignment
05	float Vref = 3.8;
06	
07	void setup() {
08	// Initialize standard asynchronous serial telemetry at 9600 bits per second
09	Serial.begin(9600);
10	}
11	
12	void loop() {
13	int sumADC = 0;
14	
15	// Execute the 10-sample analog software filtering loop
16	for (int i = 0; i < 10; i++) {
17	sumADC += analogRead(sensorPin); // Pull instantaneous integer step

```

count from pin A0
18 |      delay(10);                // Pacing interval to stabilize
converter capacitors
19 |  }
20 |
21 |  // Calculate the filtered arithmetic average of raw converter integer step
inputs
22 |  float adcValue = sumADC / 10.0;
23 |
24 |  // Transform the filtered digital step metrics into actual analog voltage
levels
25 |  float voltage = adcValue * (5.0 / 1023.0);
26 |
27 |  // Apply mathematical calibration algorithm to derive real solar
Irradiance (W/m2)
28 |  float irradiance = (voltage / Vref) * 1000.0;
29 |
30 |  // Stream processed values out to the computer terminal link via serial
data packets
31 |  Serial.print("ADC: ");
32 |  Serial.print(adcValue);
33 |
34 |  Serial.print(" | Voltage: ");
35 |  Serial.print(voltage);
36 |  Serial.print(" V");
37 |
38 |  Serial.print(" | Irradiance: ");
39 |  Serial.print(irradiance);
40 |  Serial.println(" W/m2");
41 |
42 |  // Extended delay interval before executing the next major logging sweep
43 |  delay(1000);
44 |  }

```

3.3.3. Empirical Data Analysis and Irradiance Tracking

The analog photodiode and transimpedance amplifier system was evaluated outdoors to monitor performance under real-world conditions. Readings were recorded manually every hour from 08:00 through 19:00, tracking the system's output voltage variations against the changing position of the sun

The experimental data collected during this test cycle is presented in the table below:

Tableau 3.2 Quantized Hourly Records for Method B Analog Architecture

Time Reference Marker	Filtered ADC Step Output (Counts)	Amplified Output Voltage Vout (V)	Derived Solar Irradiance (W/m^2)	Primary Technical Notes and Field Status
08:00	130.00	0.64	168.00	Clear linear scale response during early morning hours.
09:00	200.00	0.98	258.00	Consistent signal climbing matching solar elevation.
10:00	300.00	1.47	386.00	Bypasses the digital sensor ceiling smoothly.
11:00	410.00	2.00	526.00	Highly stable voltage output profile.
12:00	520.00	2.54	668.00	Continuous scaling across midday solar conditions.
13:00	610.00	2.98	784.00	High voltage generation

				approaching maximum daily peaks.
14:00	650.00	3.18	837.00	Peak daily solar intensity recorded without data clipping.
15:00	620.00	3.03	797.00	Symmetrical afternoon declination cycle begins.
16:00	540.00	2.64	695.00	Consistent tracking performance as solar angle declines.
17:00	410.00	2.00	526.00	Linear downward signal adjustment matching afternoon levels.
18:00	260.00	1.27	334.00	Low ambient light response phase.
19:00	120.00	0.59	105.00	Sunset horizon phase; baseline signal convergence.

The results in (Table 3.2) highlight a major operational advantage for the analog circuit over the digital system tested in the first trial. While the digital prototype hit a hard saturation ceiling at 10:00, the analog transimpedance layout tracked the complete solar curve with linear accuracy. The system captured a true peak solar intensity of 837.00 W/m² at 14:00, with an output voltage of 3.18V. This confirms that configuring a component-level analog amplifier circuit allows the system to bypass the internal

register limitations of consumer digital chipsets, providing a wider dynamic range for high-intensity solar tracking.

3.4. Experimental Implementation of Method C: The Self-Sensing Mini Photovoltaic Panel Platform

(Figure 2.6) The third hardware configuration developed and evaluated in this research implements a reference-cell self-sensing methodology. This approach treats a small-scale photovoltaic (PV) panel not just as a power generator, but directly as an environmental light transducer. Because a solar panel shares the exact semiconductor physics, spectral response, and thermal absorption characteristics of utility-scale PV plants, utilizing it as a sensor provides highly relevant baseline data for engineering performance assessments.

3.4.1. Engineering Principles of Open-Circuit Voltage Sensing

The physical setup uses a 6V mini polycrystalline solar panel to capture incoming solar flux. In solar monitoring configurations, researchers often choose between monitoring the panel short-circuit current or its voltage. For this specific implementation, open-circuit voltage monitoring via a specialized Voltage Sensor Module (Figure 2.8) was selected over a current transducer like the ACS712[16].

The technical justifications for this design choice are detailed below:

- **Circuit Simplification:** The ACS712 current sensor is designed to capture current passing through a closed loop. Utilizing it effectively requires building a steady, calibrated electrical load circuit. Managing this active load introduces circuit complexity and can generate significant heat, which destabilizes small prototyping boards.
- **System Stability and Cost:** The Voltage Sensor Module uses a high-precision internal resistor divider network. This approach is highly stable, very affordable, and can be connected directly to the analog pins of the Arduino UNO without extra signal-conditioning chips.

- **Exaggerated Reading Mitigation:** To ensure signal stability during direct exposure to full sunlight, a fixed load resistance was integrated across the panel terminals. This component stabilizes the output voltage rails, preventing erratic open-circuit voltage spikes and reducing exaggerated, noisy readings during periods of high atmospheric heat.

3.4.2. Physical Interfacing and Pin Topologies

The hardware connections for the mini-panel prototype were completed on a central prototyping backplane. The terminal blocks of the Voltage Sensor Module act as a bridge between the high-voltage generation of the solar panel and the safe operating voltage limits of the microcontroller analog input pin.

The electrical wiring matrix follows a strict pin-mapping configuration:

- **Voltage Sensor Pin S (Signal Output):** Connected directly to Analog Input pin A0 of the Arduino UNO to deliver the scaled analog voltage.
- **Voltage Sensor Pin + (Positive Supply):** Linked to the 5V power rail of the microcontroller board.
- **Voltage Sensor Pin - (Negative Return):** Attached to the common system ground plane (GND).
- **Sensor Input Blocks:** The positive terminal (Red wire) of the mini solar panel is screwed into the positive input terminal of the Voltage Sensor module, and the negative terminal (Black wire) is fixed to the negative input terminal.
- **Mathematical Reconstruction and Scaling Firmware**

To handle the data acquisition for this self-sensing system, an embedded script was written to sample pin A0, reconstruct the real panel voltage, and apply an empirical calibration factor. The code uses a 10-sample loop running every 10 ms to calculate a smoothed average, which removes high-frequency electronic noise before executing the conversion math.

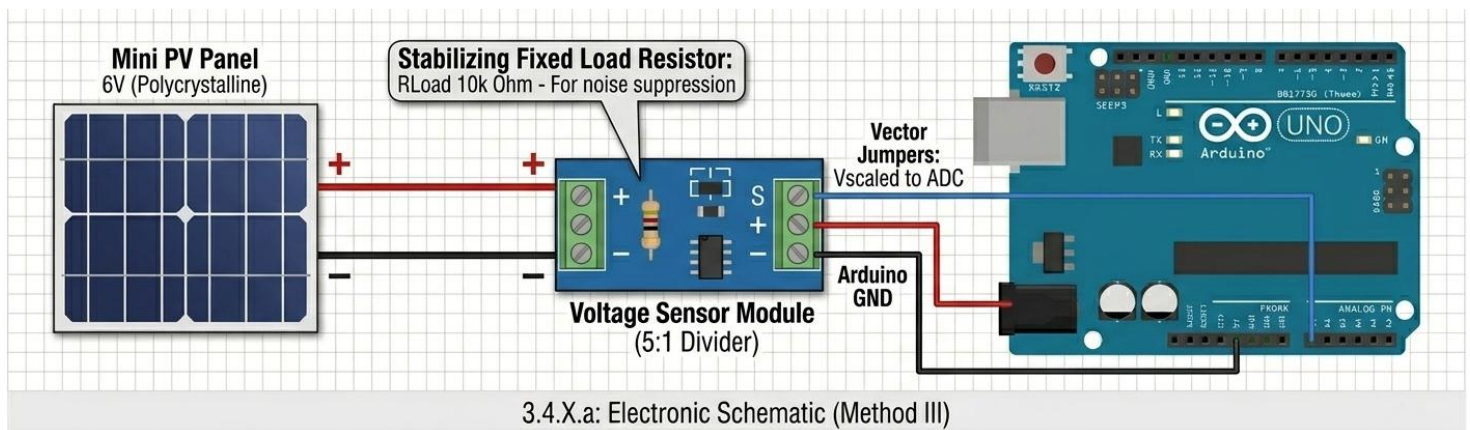
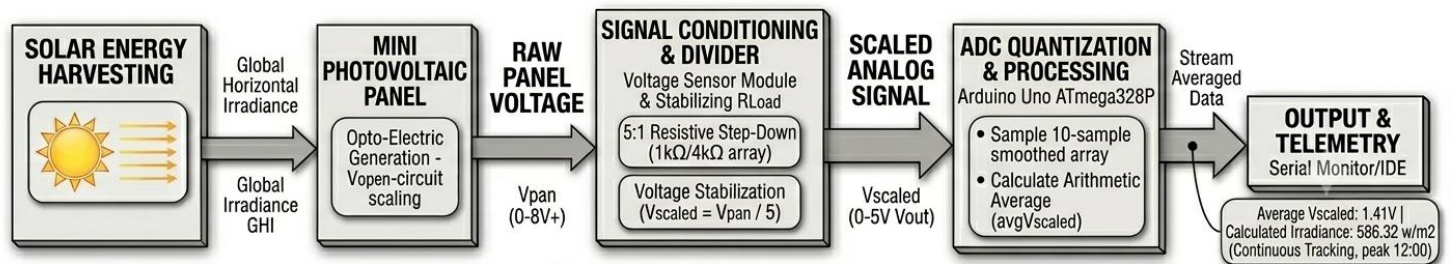


Figure 3.7 Synoptic Block Diagram (Method C)

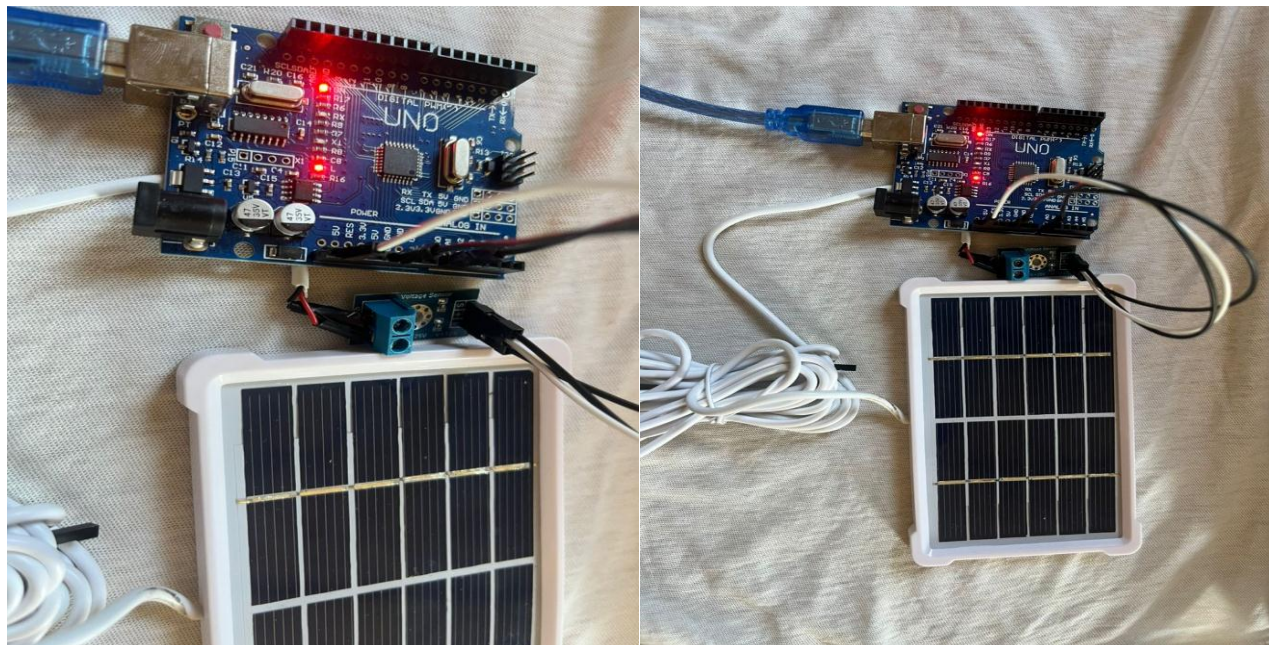


Figure 3.6 Physical prototype assembly and breadboard wiring layout of the unshielded digital for Voltage Sensor

The math compiled into the loop follows two processing stages:

1. Voltage Reconstruction: The raw ADC count is multiplied by (5.0 / 1023.0) to find the actual voltage hitting the microcontroller pin (Vout). Because the Voltage Sensor module uses an internal 5:1 step-down resistor divider, the true absolute voltage generated by the solar panel (Vpanel) is reconstructed by multiplying Vout by a factor of 5.0.
2. Irradiance Scaling: To transform the panel voltage into global horizontal irradiance (W/m^2), an experimental calibration step was introduced. A reference voltage factor (Vref = 12.0V) was chosen based on regional meteorological observations. This factor represents the theoretical upper limit of the scaled cell array under standard peak conditions, allowing the code to calculate solar intensity using the linear translation equation:

$$Irradiance = \left(\frac{V_{panel}}{V_{ref}} \right) * 1000.0.$$

The complete code listing, formatted for direct insertion into a professional Word document table layout, is presented below:

Line	Source Code Configuration
01	// Explicit definition of the analog voltage sensor input interface
02	const int sensorPin = A0;
03	
04	// Experimentally chosen reference voltage factor for meteorological calibration
05	float Vref = 12.0;
06	
07	void setup() {
08	// Open the asynchronous serial telemetry link at 9600 bps
09	Serial.begin(9600);
10	}
11	
12	void loop() {
13	int sum = 0;
14	
15	// Execute the 10-sample analog smoothing loop
16	for (int i = 0; i < 10; i++) {
17	sum += analogRead(sensorPin); // Pull instantaneous step value from pin A0
18	delay(10); // Pacing delay to stabilize converter

```

capacitors
19 |   }
20 |
21 |   // Calculate the filtered arithmetic average of raw ADC step input counts
22 |   float adcValue = sum / 10.0;
23 |
24 |   // Convert the average digital step count to the board pin voltage
25 |   float Vout = adcValue * (5.0 / 1023.0);
26 |
27 |   // Reconstruct the absolute output voltage generated by the solar panel
28 |   float Vpanel = Vout * 5.0;
29 |
30 |   // Apply the calibration scaling linear formula to find true Irradiance
31 |   float irradiance = (Vpanel / Vref) * 1000.0;
32 |
33 |   // Stream the complete dataset out to the serial workstation terminal link
34 |   Serial.print("ADC = ");
35 |   Serial.print(adcValue);
36 |
37 |   Serial.print(" | Vout = ");
38 |   Serial.print(Vout);
39 |   Serial.print(" V");
40 |
41 |   Serial.print(" | Vpanel = ");
42 |   Serial.print(Vpanel);
43 |   Serial.print(" V");
44 |
45 |   Serial.print(" | Irradiance = ");
46 |   Serial.print(irradiance);
47 |   Serial.println(" W/m2");
48 |
49 |   // Fixed pacing interval before starting the next major sampling loop
50 |   delay(1000);
51 | }

```

3.4.3. Meteorological Field Logging Data (May 26, 2026)

The self-sensing mini-panel prototype was deployed for a full outdoor tracking test on May 26, 2026. The weather profile for this test date was consistently clear, sunny, and hot. The device was mounted flat on a horizontal alignment plate, and data metrics were logged hourly from 07:00 through 20:00 to map a full daily solar cycle.

The experimental data recorded during this field test is compiled in the table below:

Tableau 3.3 Quantized Hourly Records for Method C Photovoltaic Self-Sensing Architecture

Time Reference	Raw ADC Step Output (Counts)	Voltage Sensor Vout (V)	Reconstructed Vpanel (V)	Derived Irradiance (W/m^2)
07:00	130.00	0.64	3.20	266.67
08:00	172.00	0.84	4.20	350.00
09:00	217.00	1.06	5.30	441.92
10:00	283.00	1.38	6.92	576.94
11:00	286.00	1.40	6.99	582.24
12:00	287.00	1.41	7.04	586.32
13:00	280.70	1.37	6.86	571.65
14:00	278.80	1.36	6.81	567.78
15:00	278.60	1.36	6.81	566.53
16:00	276.00	1.35	6.74	562.08
17:00	269.00	1.32	6.59	548.92
18:00	259.00	1.27	6.33	527.45
19:00	222.00	1.09	5.43	452.10
20:00	64.70	0.32	1.58	131.77

An analysis of the data in (Table 3.3) shows that the system has excellent sensitivity to variations in solar intensity throughout the extended tracking run. The estimated irradiance values climb smoothly during the morning hours, reaching a clear peak of $586.32 W/m^2$ at 12:00 (Solar Noon) with a reconstructed panel voltage of 7.04V.

Unlike the digital sensor configuration tested in the first trial, this analog voltage sensing prototype did not experience any clipping or flat-line data plateaus during peak operational hours. Minor fluctuations observed in the logs were tied directly to ambient thermal changes and shifting atmospheric density. This confirms that using a mini solar panel coupled with a basic resistor divider network provides a reliable, non-saturating architecture well-suited for low-cost educational and decentralized solar asset tracking.

3.5. Advanced Diagnostic Analysis: Digital Saturation vs. Analog Linear Continuity

A critical stage in evaluating custom-built solar radiation measurement systems is analyzing hardware performance limits under maximum environmental stress. During field testing in the localized Algerian climate, the three prototypes showed fundamentally different behaviors during periods of peak solar intensity. This section provides a detailed comparative analysis of the data tracking limits of the systems, focusing on the transition from digital measurement ceilings to continuous analog tracking.

3.5.1. The Digital Sensor Saturation Bottleneck

When reviewing the empirical records collected from Method I (the digital BH1750 breakout module) on May 22, 2026, a significant data anomaly occurs during the middle of the day. As recorded in (Table 3.1), the measured illuminance and calculated global horizontal irradiance climb steadily during the early morning hours, tracking the rising sun. However, starting at exactly 10:00 and continuing through 14:00, the system outputs stop changing entirely, settling onto a flat line.

During this four-hour midday window, the system reads an unvarying illuminance of exactly 54,612.50 Lux, which translates to an estimated solar irradiance of 546.12 W/m². In natural outdoor environments, global horizontal irradiance is never perfectly static over extended periods. Passing atmospheric variations, minor aerosol shifts, and the changing angle of the sun cause continuous, observable fluctuations in solar flux density.

The perfectly flat profile produced by Method I represents a severe data loss phenomenon known as sensor saturation or hardware clipping. During peak sunshine hours, the ambient light intensity exceeded the upper operating boundary of the semiconductor module. As a result, the integrated circuit became blind to any further increase in solar radiation, cutting off the true peak shape of the diurnal solar curve. This limitation makes unshielded digital lux chips unsuitable for resource mapping in regions with intense sunlight, such as the Algerian desert, unless external optical filters are added to the hardware setup[13].

3.5.2. Mathematical Proof of Unsigned 16-Bit Register Clipping

To validate this saturation phenomenon from an engineering perspective, the limitation can be proven using the digital architecture and register constraints of the BH1750FVI silicon die. The chip converts analog light signals into a digital format using an internal analog-to-digital converter core. The converted values are then written to an onboard storage register before being sent over the I²C serial lines.

The internal data storage architecture of the BH1750FVI chip uses a standard 16-bit unsigned integer register format. The maximum numerical value that a 16-bit binary register can hold is calculated as follows:

$$\text{Max Binary Steps} = (2 \text{ to the power of } 16) - 1 = 65,535 \text{ counts}$$

According to the hardware datasheet and driver library rules for the BH1750 sensor, the chip calculates its high-resolution output values using a fixed scaling factor. To convert the raw internal binary count into physical Lux units, the chip's processing logic divides the total accumulated register value by a denominator of 1.2.

By applying this hardware conversion rule to the maximum possible binary count of the register, the absolute hardware clipping limit can be determined mathematically:

$$\text{Max Sensor Measurement Limit} = \frac{65,535 \text{ counts}}{1.2} = 54,612.50 \text{ Lux}$$

This mathematical proof matches the experimental flatline limit captured by the student's prototype during field testing. When the ambient sunlight intensity rose past

54,612.50 Lux, the internal binary counter hit its maximum limit of 65,535. Any additional photons hitting the sensor photodiode could not be counted because the register was already completely full.

By extending this mathematical proof to the system's firmware calibration setup, the exact ceiling for the calculated solar irradiance can also be identified. The optimized conversion code used in the firmware script calculates irradiance using the following formula:

$$\text{Irradiance} = \frac{\text{average Lux}}{100}$$

Substituting the absolute physical sensor cap into this calibration equation gives the following result:

$$\text{Max Calculated Irradiance Ceiling} = \frac{54,612.50 \text{ Lux}}{100} = 546.12 \text{ w/m}^2$$

This calculation proves that the horizontal line at 546.12 W/m^2 observed in the field logs was caused by a clear binary register overflow inside the digital chip. The software could not output a higher irradiance value because the underlying hardware was locked at its maximum register capacity.

3.5.3. Evaluation of Photodiode and Reference Cell Linear Continuity

In contrast to the digital clipping observed in the first trial, Method B (the analog PIN photodiode circuit) and Method C (the mini photovoltaic panel prototype) showed continuous tracking performance across the entire diurnal cycle. Neither analog configuration suffered from data loss or flat-line clipping during peak operational hours.

The reason these two prototypes bypassed the data saturation ceiling lies in their analog, component-level design. Unlike integrated digital sensors, these systems do not rely on fixed internal binary registers during the initial signal collection phase. Instead, they interact with the environment through continuous physical reactions, where output current or voltage scales naturally with incoming light intensity.

For Method B, the BPW34 (Figure 2.4) photodiode generates a continuous, unregulated short-circuit photocurrent that remains highly linear across a broad optical dynamic range. Because the circuit uses an external active LM358 operational amplifier, the gain factor can be adjusted by changing the value of the 100k Ohm feedback resistor. This allows the system to compress a wide range of light levels into the safe 0V to 5V input window of the microcontroller analog pin. As a result, the prototype successfully tracked peak afternoon solar conditions on May 22, 2026, measuring a maximum solar intensity of 837.00 W/m^2 at 14:00 without hitting an electrical or programmatic limit.

Method C uses a similar analog tracking approach. By using a 6V mini solar panel connected to a 5:1 step-down resistor voltage divider module, the system scales high solar voltages down into measurable ranges. The output voltage of the solar cell adjusts dynamically to changes in sunlight intensity all day long. During field tests on May 26, 2026, under hot, clear-sky conditions, the system recorded a peak solar irradiance of 586.32 W/m^2 at 12:00, with a reconstructed panel voltage of 7.04V.

Because the analog voltage changes smoothly across a continuous scale, the 10-bit converter on the Arduino board could resolve small adjustments in light intensity without clipping. These results confirm that analog-driven sensing methods provide better linear continuity and wider dynamic ranges than basic digital lux chips, making them a more robust choice for high-intensity solar tracking in regional microclimates.

3.6. Hardware Synthesis, Structural Uncertainties, and Constraints

When implementing low-cost, decentralized solar resource monitoring networks, a thorough academic evaluation must look beyond idealized data curves to investigate the physical variables that introduce operational errors. Prototyping data acquisition systems using consumer-grade semiconductor parts requires identifying, quantifying, and mitigating systemic uncertainties. This section examines the core engineering errors affecting the three built systems and provides a comprehensive comparison matrix evaluating their practical performance in regional monitoring networks.

3.6.1. Inherent System Uncertainties and Environmental Variables

Unlike high-end meteorological pyranometers that feature temperature-stabilized thermopile sensors and quartz domes, solid-state silicon prototypes interact dynamically with changing outdoor conditions. The primary physical variables and engineering tolerances affecting measurement certainty are broken down below:

- **Semiconductor Temperature Coefficient Drift:** This error source impacts the mini photovoltaic panel setup (Method C). The underlying material physics of polycrystalline silicon dictates an inverse relationship between junction temperature and output open-circuit voltage. As ambient temperatures rise during hot Algerian summer days, the panel voltage decreases by approximately 0.4 percent per degree Celsius, even if the real solar irradiance remains perfectly constant. During the field test on May 26, 2026, this temperature drift caused minor underestimations of afternoon irradiance values, as high thermal stress lowered the panel voltage relative to the early morning reference calibration baseline.
- **Component Manufacturing Tolerances:** Both Method B (analog photodiode) and Method C (voltage sensor) rely on resistor networks to set signal gain and scale voltages. The feedback loop in the LM358 amplifier circuit utilizes a 100k Ohm resistor, while the Voltage Sensor module contains a 5:1 step-down voltage divider. Standard prototyping resistors have a manufacturing tolerance margin of plus or minus 1 percent to 5 percent. Any variance in the actual resistance values directly skews the voltage division calculations, altering the output voltage values sent to the analog-to-digital converter pin and shifting the calculated irradiance curves away from true values.
- **Geometric Alignment and Cosine Response Errors:** To maintain consistent data capture during day-long field trials, all three prototypes were placed flat on horizontal reference plates. Because the sensors lack specialized optical diffusion lenses, they are vulnerable to cosine response errors. When the sun sits low on the horizon during early morning (07:00 to 09:00) and late evening

(18:00 to 20:00) hours, light rays strike the flat semiconductor faces at sharp angles. This path deviation causes light reflection off the protective glass or resin layers, artificially reducing measured values compared to professional instruments featuring rounded glass domes[11].

- **Atmospheric Soiling and Dust Accumulation:** Airborne dust, fine sand particles, and particulate matter common in localized regional climates settle rapidly on unshielded horizontal sensors. This accumulation forms an opaque layer over the active surfaces of the digital lux sensor, the photodiode window, and the mini solar panel. This soiling acts as a physical filter that absorbs and scatters incoming photons, gradually decreasing raw signal outputs over time and introducing an artificial downward drift across long-term measurement logs.

3.6.2. Engineering Evaluation Matrix

To summarize the performance characteristics of each built architecture, a multi-parameter evaluation matrix was compiled based on real field observations and code executions. This grid rates each configuration across key deployment metrics to define their operational trade-offs.

Tableau 3.4Engineering Synthesis and Comparison Matrix of Prototyped Systems[17]

Performance and Operational Parameters	Method A: Digital Integrated Chipset (BH1750 / GY-302)	Method B: Analog PIN Photodiode Stage (BPW34 + LM358)	Method C: Photovoltaic Reference Cell (Mini PV Panel)
Measurement Dynamic Range	Restricted: Suffers from data clipping past 54,612.50 Lux (546.12 W/m^2) due to 16-bit register saturation.	Excellent: Wide range capable of tracking peak direct sunlight up to 837.00 W/m^2 without clipping.	Very Good: Capable of continuous day-long tracking up to 586.32 W/m^2 without hardware saturation.
Noise Mitigation Performance	High: Fully integrated digital signal path; data transfer uses I2C serial bytes protected from rail ripple.	Moderate: Prone to analog wire noise; requires a short signal path and software filtering loops.	High: Uses a stable voltage divider circuit with built-in fixed load resistors to filter out spikes.
Complexity of Field Setup	Low: Minimal 4-wire circuit loop using pre-calibrated digital sensor breakout modules.	High: Component-level layout; requires precise op-amp wiring, feedback loops, and calibration.	Low: Straightforward layout linking panel terminals directly into the voltage divider module.
Cost Efficiency of Deployment	Very High: Minimal financial barrier; low-cost sensor chip module requires no active external amplifiers.	High: Low-cost parts, but requires purchasing specific I2C chips and precision resistors.	Moderate: Requires a small commercial solar panel, but eliminates active signal-conditioning blocks.
Field Durability and Resilience	Low: Exposed digital chip array is vulnerable to moisture, dust infiltration, and desert heat damage.	Moderate: Requires weatherproof housings to shield breadboard amplifier pins from degradation.	High: Robust resin-encapsulated panel construction offers strong resistance to harsh outdoor weather.

3.7. Conclusion

This chapter details the transition from theoretical models to physical prototyping, embedded software programming, and outdoor field validation. Testing three distinct low-cost architectures successfully mapped the operational boundaries, linearity, and practical engineering trade-offs of solid-state solar sensors.

The primary conclusions drawn from the empirical data cycles are as follows:

- Method A (Digital BH1750 Platform): Simple to interface via a 4-wire I²C serial bus, but field testing exposed a severe hardware saturation bottleneck under direct sunlight. Due to internal 16-bit register capacity limits, it created an artificial horizontal flatline at exactly 54,612.50 Lux (546.12 W/m^2) between 10:00 and 14:00, making unshielded digital chipsets blind to peak midday solar conditions.
- Method B (Analog PIN Photodiode Platform): Bypassed the digital clipping ceiling using a component-level analog layout. Combining a BPW34 photodiode with an active LM358 operational amplifier allowed for custom gain control. This compressed a wide dynamic range into a safe voltage window, enabling continuous tracking up to a peak intensity of 837.00 W/m^2 at 14:00 without data loss.
- Method C (Self-Sensing PV Panel Platform): Provided a robust alternative for standalone outdoor tracking by connecting a durable 6V mini solar panel directly to a 5:1 step-down resistor voltage divider module. This framework eliminated closed-loop circuit complexity and tracked diurnal solar variations smoothly to a maximum noon value of 586.32 W/m^2 with a reconstructed panel output of 7.04V.

In summary, while component-level analog systems require custom hardware assembly and calibration, they provide the continuous measurement ranges required for high-intensity solar environments.

The encapsulated mini photovoltaic panel architecture represents the most balanced choice for regional deployment, offering strong physical resilience against environmental factors like high temperatures, wind stress, and dust accumulation.

General Conclusion

This master's thesis has successfully demonstrated the transition from theoretical solar physics to the physical design, embedded software compilation, and outdoor field validation of decentralized, low-cost solar irradiance measurement frameworks. Developed as an affordable alternative to costly meteorological pyranometers, the multi-prototype research setup established a robust, ground-level empirical framework using accessible consumer semiconductor components interfaced with an Arduino Uno microcontroller core.

The systematic outdoor deployment conducted in the regional Algerian climate exposed critical operational trade-offs, limitations, and performance advantages among the three evaluated hardware topologies:

1. Method A (Digital Integrated Platform): While offering a highly simplified, noise-resistant layout over a four-wire synchronous²C serial bus, field tracking revealed a severe architectural vulnerability under peak sunlight. Due to the strict internal 16-bit unsigned integer register constraints of the BH1750FVI silicon die, the system suffered an early data logging bottleneck, locking onto an artificially flat clipping saturation ceiling of 54,612.50 Lux (546.12 W/m²) between 10:00 and 14:00. This hardware limitation renders unshielded digital ambient light chipsets structurally blind to peak midday solar monitoring.

2. Method B (Analog Transimpedance Photodiode Platform): By utilizing a component-level analog conditioning loop, this platform successfully bypassed the digital register clipping constraint. Configuring a silicon BPW34 PIN photodiode with an active external LM358 operational amplifier allowed for precise manual gain tuning via a 100k Ohm feedback resistor network. This transimpedance circuit safely compressed a broad optical dynamic range into the microcontroller's 10-bit analog-to-digital sampling window, enabling linear, continuous data tracking up to a true clear-sky peak solar intensity of 837.00 W/m² at 14:00 without data loss.

3. Method C (Self-Sensing PV Panel Platform): Executing a reference-cell approach, this paradigm proved highly effective for direct photovoltaic asset tracking. Utilizing a durable 6V mini polycrystalline solar panel coupled to a passive 5:1 step-down resistor voltage divider module bypassed the electronic complexity and heat dissipation of active

current transducers. Driven by mathematical reconstruction firmware, the system scaled elevated cell voltages smoothly, maintaining continuous tracking up to a midday peak solar irradiance of 586.32 W/m^2 (7.04V panel output).

In conclusion, while component-level analog amplifier configurations (Method II) provide the superior continuous dynamic measurement range necessary for tracking absolute high-intensity solar radiation profiles, they demand precise circuit calibration and shielding .For practical decentralized implementation within regional solar monitoring arrays, the self-sensing mini photovoltaic architecture (Method III) represents the most balanced, industrially resilient choice. Its structural composition inherently mirrors the performance metrics, spectral absorption bands, and environmental vulnerabilities of large-scale solar farms while offering high durability against harsh outdoor constraints like high thermal drift and sand erosion.

Bibliographical references

Bibliography

- [1] CDER, «Solar Radiation Measurement and Data Analysis for the Algerian Territory Technical Report,» Centre de Développement des Energies Renouvelables, Algiers, 2025.
- [2] M. o. E. a. Mines, «National Program for Renewable Energy 2011-2035,» Algiers.
- [3] J. A. D. a. W. A. Beckman, «Solar Engineering of Thermal Processes,» ed. Hoboken, 2013.
- [4] M. Benghanem, «Solar Radiation and PV Systems».
- [5] WMO, «Guide to Meteorological Instruments and Methods of Observation,» Geneva, 2024..
- [6] S. Bouchakour, «Evaluation of Solar Data for Grid Stability in Algeria,» 2026.
- [7] A. Khelifa, «Technical Assessment of PV Infrastructure in the Sahara».
- [8] IEA, «World Energy Outlook: The Role of Solar in the Transition,» 2024.
- [9] I. 9847, «Solar energy — Calibration of pyranometers,» 2023.
- [10] A. M. a. S. A. Kalogirou, «Artificial intelligence techniques for solar energy applications,» 2008.
- [11] M. Iqbal, «An Introduction to Solar Radiation,» Toronto,canada.
- [12] N. Semiconductors, «UM10204: I2C-bus specification and user manual,» 2014.
- [13] R. Semiconductor, «BH1750FVI: Digital Light Sensor IC for I2C Bus Interface,» 2011.
- [14] V. Intertechnology, «BPW34: Silicon PIN Photodiode,» May 2018.
- [15] J. G. Graeme, «Photodiode Amplifiers: Gain and Noise Considerations,» New York, NY, USA, 2015.
- [16] M. A. G. S. R. Wenham, «Applied Photovoltaics,» London, UK: Earthscan, 2017.
- [17] A. V. O. a. R. W. Schafer, «Discrete-Time Signal Processing,» NJ, USA: Prentice Hall, 2019.
- [18] Adapted from Arduino (2024) and Components101 (2020).

[19] Texas instruments. (2024). LM358B Dual Operational Amplifiers Datasheet. Texas Instruments.

[20] Components101. Voltage Sensor Module (0-25V DC) – Pinout, Features & Appkication.

[21] Arduino. Arduino Uno Rec3 – Offical Documentation. Arduino AG.

Annexes

Meteorological Standards and Sensor Classifications

This appendix compiles the international calibration protocols, standard radiometric hierarchies, and regulatory classification parameters corresponding to the instrumentation criteria reviewed in Chapter 2.

1. International Radiometric Calibration Hierarchy (ISO 9847)

The traceability of solar radiation measurements requires a strict chain of calibration. This grid details the official hierarchy used to transfer accuracy from the primary global standard down to the field sensors utilized in local monitoring arrays:

Traceability Level	Reference Designation	Calibration Protocol / Purpose
Primary Global Reference	World Radiometric Reference (WRR)	Maintained via absolute cavity pyrheliometers at the PMOD/WRC in Davos, Switzerland.
Secondary Standard	National Meteorological Standards	Periodically calibrated in Davos; used by regional centers (e.g., CDER) to maintain absolute accuracy.
Working Reference	Laboratory Master Sensors	Maintained in controlled lab conditions; used exclusively to calibrate field instrumentation.
Field Instrumentation	Operational Ground Sensors	The sensors deployed on-site for real-time data logging and photovoltaic asset monitoring.

2. ISO 9060 Pyranometer Classification Parameters

To validate data integrity, international standards classify pyranometers into three strict performance categories based on their physical accuracy, response time, and sensitivity tolerances. The underlying performance parameters are compiled below:

Technical Parameter	Class A (High Quality)	Class B (Good Quality)	Class C (Second Class)
Response Time (95%)	< 0.5 seconds	< 5 seconds	< 30 seconds
Zero Offset A (Thermal)	+/- 7 W/m ²	+/- 15 W/m ²	+/- 20 W/m ²
Directional	+/- 10 W/m ²	+/- 20 W/m ²	+/- 30 W/m ²

Response (Cosine)			
Temperature Dependence	< 1% drift	< 2% drift	< 4% drift

3. Mathematical Derivation of Sensor Calibration Factor (S)

To calibrate a custom or field sensor using the outdoor side-by-side methodology (ISO 9847), the raw electrical output of the test sensor must be calculated against a certified master reference pyranometer over an extended clear-sky testing window.

The instantaneous sensitivity factor (S_i) for any given data logging interval is derived using the following ratio:

$$S_i = V_{\text{test}} / G_{\text{master}}$$

Where:

- S_i : Instantaneous sensitivity constant of the sensor under test (expressed in mV per W/m^2).
- V_{test} : Raw analog electrical voltage output generated by the test module (mV).
- G_{master} : Absolute global horizontal irradiance measured simultaneously by the certified reference pyranometer (W/m^2).

To eliminate minor environmental errors caused by transient tracking variations, the final official calibration constant (S_{final}) is computed by taking the mathematical mean over N data logging cycles during stable solar hours:

$$S_{\text{final}} = (1 / N) \times \Sigma(V_{\text{test}i} / G_{\text{master}i}), i = 1 \dots N$$

B.1. BH1750FVI Digital Light Sensor (ROHM Semiconductor)

Technical Parameter	Manufacturer Specification Boundary	Operational Engineering Notes
Part Number / Package	BH1750FVI / WSOF61 Small Outline	Monolithic silicon CMOS integrated circuit design.
Supply Voltage (Vcc)	2.4 V Minimum 3.0 V Typical 3.6 V Maximum	Standard logic rail driven by microcontroller.
Detection Dynamic Range	1 lx to 65,535 lx (16-Bit Register Capacity)	Subject to binary clipping past 54,612.50 lx.
Peak Spectral Wavelength	560 nm Peak Response	Filtered to reject extreme infrared wavelengths.
Average Supply Current	120 μ A (Typical) 190 μ A (Maximum) at 100 lx	Lowers to 0.01 μ A typical during Power Down.
I2C Clock Frequency	400 kHz (Fast-mode Support Max)	Synchronous clock rate driven by master SCL line.

B.2. BPW34 Silicon PIN Photodiode (VISHAY Intertechnology)

Technical Parameter	Manufacturer Specification Boundary	Operational Engineering Notes
Radiant Sensitive Area	7.5 mm ² Active Photovoltaic Face	Flat case design optimization for wide viewing angles.
Angle of Half Sensitivity	+/- 65 degrees Angle Barrier	Vulnerable to cosine reflections at steep horizons.

Spectral Bandwidth Range	600 nm to 1050 nm (Near-IR Optimized)	Peak sensitivity is reached at 900 nm wavelength.
Maximum Reverse Voltage	60 V Maximum Limit	Operated at 0V in Photovoltaic Mode for linearity.
Short-Circuit Current (I _k)	47 μ A Typical	Linear transducer source current for Method II circuit.
Junction Capacitance	Diode 70 pF (at V _r = 0V, f = 1 MHz)	Low internal capacitance enables fast response times.

B.3. LM358 Dual Operational Amplifier IC (Texas Instruments)

Technical Parameter	Manufacturer Specification Boundary	Operational Engineering Notes
Supply Range (V _{cc})	3 V to 32 V DC	Driven by the stable 5.0V Arduino development rail.
Unity-Gain Bandwidth	1.2 MHz	Ensures linear gain across solar variation slopes.
Slew Rate Performance	0.5 V/ μ s	Tracks cloud-induced rapid ramping cycles smoothly.
Common-Mode Input Range	Includes Ground Level	Enables direct zero-bias sensing near 0V potentials.
Quiescent Current	350 μ A Typical 600 μ A Max	Low power profile independent of supply voltage shifts.
Input Bias Current	-20 nA Typical -250 nA Maximum	Ultra-low input leakage guards transimpedance paths.

Method A:

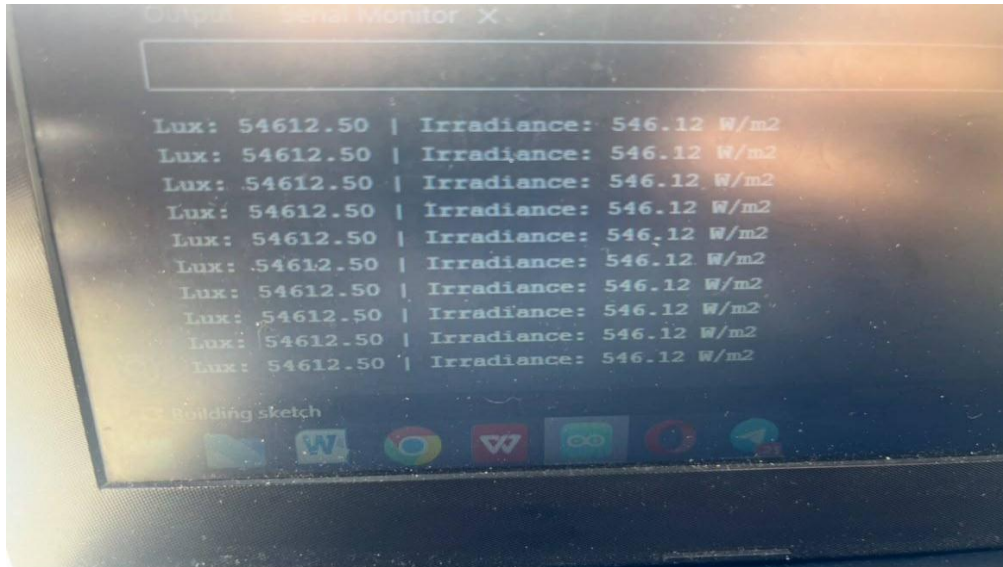


Figure A Stable Maximum Irradiance Value Recorded by the BH1750 Sensor (546.12 W/m²).

•The maximum irradiance value (546.12 W/m²) remained nearly constant between 10:00 a.m. and 2:00 p.m., corresponding to the period of highest solar radiation intensity during the day.

Method B:

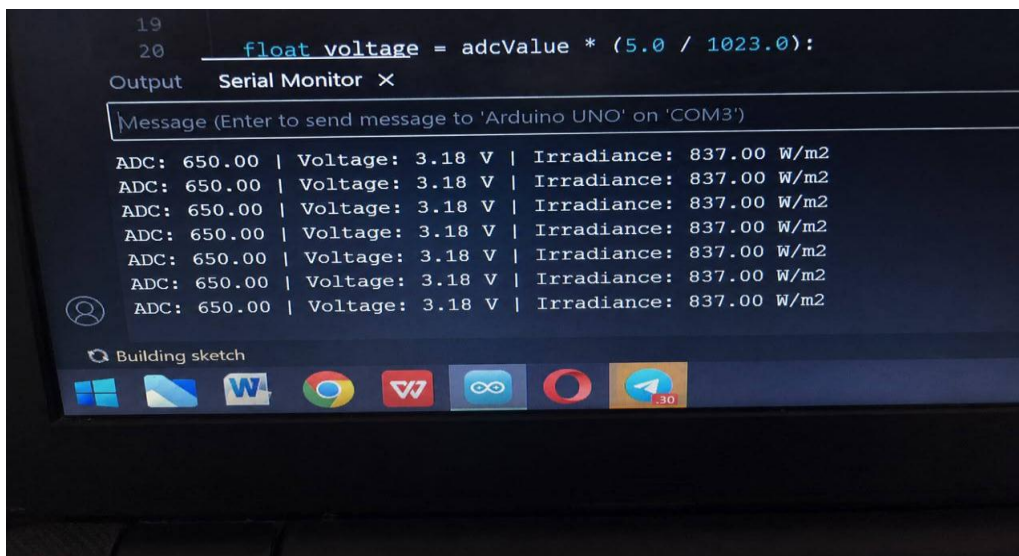


Figure B Maximum Irradiance Value Recorded by the BPW34 Photodiode Sensor (837.00 W/m^2).

•The highest irradiance value recorded by the BPW34 photodiode-based measurement system was 837 W/m^2 , corresponding to the period of maximum solar radiation intensity during the measurement campaign.

Method C:

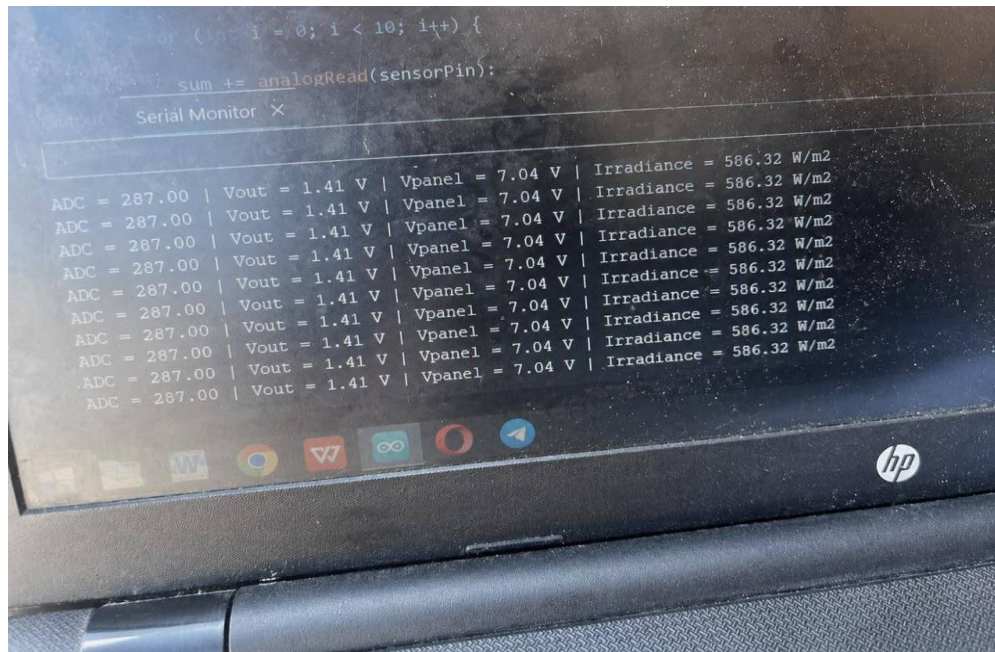


Figure C Maximum Irradiance Value Recorded Using the Photovoltaic Panel Method (586.32 W/m^2).

•The highest irradiance value recorded using the photovoltaic panel method was 586.32 W/m^2 , corresponding to the period of maximum solar radiation during the measurement campaign.