University of Padova
Department of Management and Engineering DTG
Master's Thesis in Management Engineering

Experimental analysis of the behavior and energy yield of different types of photovoltaic modules and brief comparisons with the responses of various types of irradiance sensors

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Abstract

In this thesis, we are conducting a study on two types of Photovoltaic modules namely bifacial and half cut which are commercially used currently. Their performances were measured in two ways: the first was simply by noting the daily productions of each module technology, in the second case performance ratio measurement was done using two different types of pyranometer sensors namely Photovoltaic pyranometer and Thermopile pyranometer. These experimental activities were carried out under different time periods of the day in order to compare the effect of the Sun's irradiance level on the performance ratio.

Summary

In this thesis, the Performance ratio of Two types of Photovoltaic modules namely bifacial photovoltaic (PV) modules and half cut PV modules were studied numerically and experimentally, using two different types of pyranometers namely Photovoltaic pyranometer and Thermopile pyranometer.

In the current global scenario, global warming and fossil fuel scarcity are the biggest problems faced by mankind which is caused due to severe rise in the CO_2 emissions in the atmosphere. In order to reduce the CO_2 emission, nations across the world are taking initiatives, providing support and rewards to promote the usage of renewable energy sources for both residential and industrial power consumers.

The most common renewable energy sources are wind energy, solar energy, bioenergy and hydroelectric, including tidal energy among which solar energy is used widespread in domestic and industrial power generation. Solar Energy is produced using Photovoltaic modules which converts photons into electric current.

The main concerns for the consumers about setting up a photovoltaic module is the selecting the right type of PV module which provides a better performance ratio which in turn maximize the Return on Investment (ROI) during a certain time span and selecting the right type of pyranometer sensor which measures the irradiation values of the sun which is useful in calculating the performance ratio of the PV module.

Therefore, we are comparing two different types of Photovoltaic modules namely Bifacial PV module and half cut PV module by measuring their performance ratio using two different types of pyranometers namely Photovoltaic pyranometer and Thermopile pyranometer.

Successively it is explained how the experimental setup was planned and built. Initially it was decided the number of PV modules for each type and the position, location and angle of the experimental setup.

Each type of PV module was connected to the dedicated micro inverters which is used to convert the DC current into AC current which is the type of current used by all the electric appliances. Using this, the actual power generated by the PV modules are noted.

Simultaneously, Pyranometers are placed in the same plane of the PV modules in order to measure the irradiation value which is used to calculate the theoretical power generation value. The measurement values are obtained from the pyranometers using a device called dataloggers which transfers the data to a computer during every fixed time interval. Data can be read directly in the computer or can be uploaded in a web portal for remote monitoring.

The tests were carried out during the different times of the day with varying intensity of the sun's irradiation levels. The raw experimental data was obtained using which the performance ratio was calculated. Uncertainty values were also evaluated and calculated during this phase. Results are entered in a table and plotted on a graph for visual representation.

The principal observations are :-

- In the comparison between the energy production efficiencies of the two types of PV modules namely Bifacial PV module and Halfcut PV module, from this study it is observed that the Bifacial PV module is 7.92% more efficient in energy production.
- In the comparison between the accuracy between the two types of pyranometer sensors namely Photovoltaic pyranometer and Thermopile pyranometer, from this study it is observed that the Photovoltaic pyranometer is 3.85% more accurate in measuring the energy production.

Other future possibilities :-

- More different types of PV modules can be compared and studied.
- The experimental setup can be studied at different times of the year to understand the effect of seasons.
- The experimental setup can be studied at different geographical locations to understand the effect of location.
- Effect of different types of ground surfaces can be studied for Bifacial PV modules.

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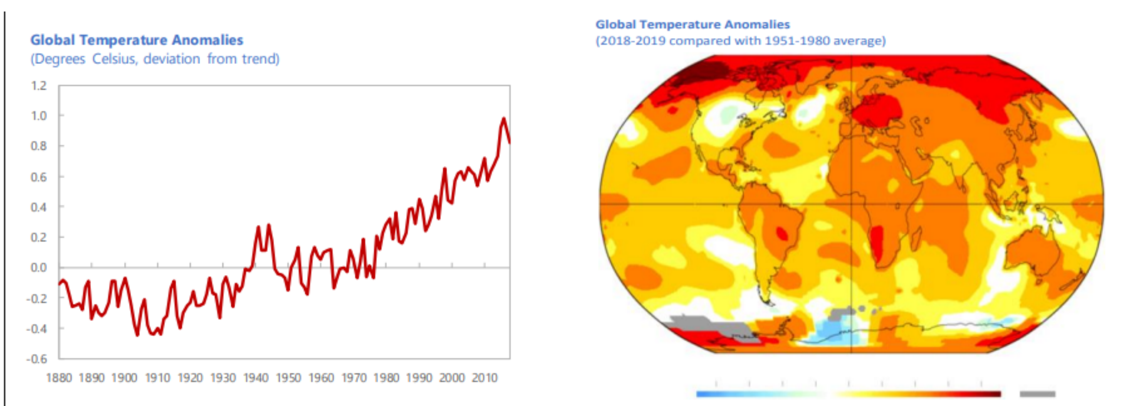
Introduction

Climate change is accelerating rapidly, with a narrow possibility to escape its worst environmental and socioeconomic consequences. The global average surface temperature has already increased by about 1.1 degrees Celsius (°C) compared with the preindustrial average during 1850–1900, amplifying the frequency and severity of climate shocks across the world (Figure 1). The risk of extreme weather events, such as heat waves, wildfires, droughts, flooding, and severe storms, is projected to increase over the next century, as the global mean temperature continues to rise by as much as 4°C over the next century (IPCC 2007, 2014, 2019; 2021). According to the latest assessment, if greenhouse gas (GHG) emissions remain on the current growth path, global warming is projected to reach 4-6°C by 2100—an unprecedented shift with greater probability of larger and irreversible environmental changes unseen in millions of years that threaten devastation in swathes of the natural world and render many areas unlivable. Although 189 countries have committed to reduce carbon dioxide (CO_2) emissions by 30 percent in 15 years until 2030, global CO_2 emissions continued to increase since the 2015 Climate Accord by 2.3 percent to 36.3 billion metric tons in 2021—the highest level in history.



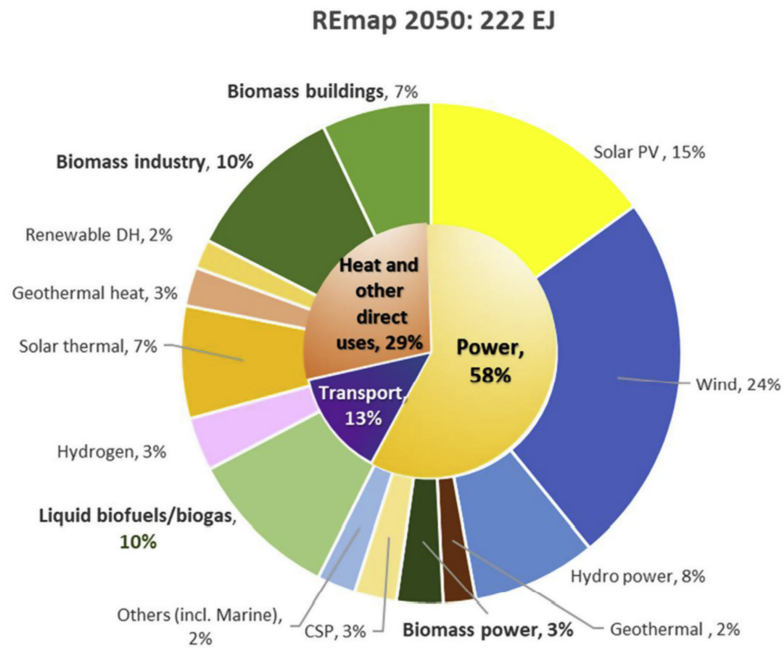
Source: NOAA.

Figure 1.1 : Global Climate Change

Moving away from fossil fuels is certainly necessary to mitigate climate change, and that requires global CO_2 emissions to peak by 2025 and reach net zero by 2050. Unfortunately, the current pace of CO_2 emissions is still not consistent with the goals of the Paris agreement (IPCC, 2021). Using a panel of 39 countries in Europe over the period 1980–2019, the empirical analysis presented in this paper finds that increasing the share of nuclear, renewables, and other non-hydrocarbon energy and improving energy efficiency could contribute to a significant reduction in CO_2 emissions and imported sources of energy. The results show that the share of non-hydrocarbon sources of energy and energy efficiency are associated with lower CO_2 emissions and energy imports in the long run, after controlling for economic, demographic, and institutional factors. These statistically significant effects are particularly more pronounced in emerging European economies, indicating potentially substantial gains in both environmental outcomes and energy security. **[1]**

A global energy transition is urgently needed to meet the objectives of limiting average global surface temperature increase below 2° Celsius. The implications of the Paris agreement for the energy sector will be profound to an extent that is not yet fully captured by existing energy scenarios . A transition away from fossil fuels to low-carbon solutions will play an essential role, as energy-related carbon dioxide (CO_2) emissions represent two-thirds of all greenhouse gasses (GHG). This energy transition will be enabled by technological innovation, notably in the field of renewable energy. Record new additions of installed renewable energy power capacity can be attributed to rapidly falling costs and competitiveness, particularly for solar photovoltaics (PV).

In terms of power generation, renewables have accounted for more than half of all global capacity additions since 2012. In 2017, newly installed renewable power capacity in the world achieved a new record of 167 GW. This was another record year where more than 60% of all new electricity capacity was from renewables. Solar PV capacity has experienced a growth more than any other source of electricity generation . Global new investment in renewables amounted to USD 241.6 billion in 2016; 2017 was the fifth consecutive year that new investment in renewable power generating capacity was roughly double the one in fossil power generation capacity. At the root of this acceleration are substantial reductions in renewable technology costs. The levelized cost of electricity from solar photovoltaics has fallen by an astounding 73% between 2010 and 2017. IRENA analysis estimates that by 2020, all renewables technologies currently in commercial use will be cost-competitive with fossil-fuels in many parts of the world, and even undercut them significantly in many cases. World-wide recent tenders have resulted in record-breaking prices: in recent years utility scale solar PV projects are offered at US cents 2–3 per kWh under the best conditions. These prices are below this of conventional fossil and nuclear generation, in some cases even below the operating cost of existing conventional plant.**[2]**



[2]

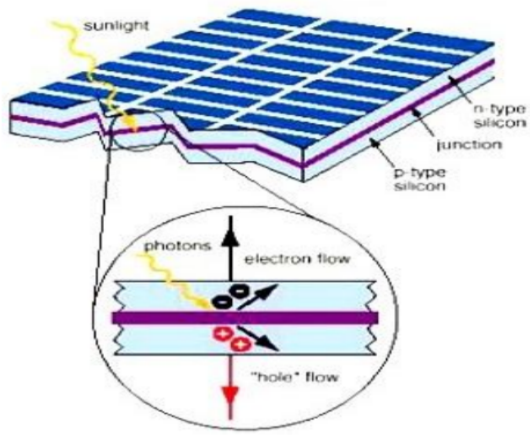
Figure 1.2 : Breakdown of renewables use in total final energy consumption terms, REmap 2050.

1.1 Solar PV

Solar PV power is safe and reliable, no noise, no pollution, less constrained, low failure and convenient maintenance etc. It is very important in alleviation of the increasingly serious energy crisis and environmental pollution. Since the energy crisis in 1970s, each country of the world has paid more attention on development of PV power generation, such as Million Solar Roofs Initiative of the United States, Sunshine Program of Japan , Million solar roofs program of Germany, and the Bright Project of western province without electricity of China as the representatives of PV power technology development and rapid application development . **[3]**

Everyday earth receives sunlight above (1366W approx.) This is an unlimited source of energy which is available at no cost. The major benefit of solar energy over other conventional power generators is that the sunlight can be directly converted into solar energy with the use of the smallest photovoltaic (PV) solar cells.

Amount of energy in the form of heat and radiation is called solar energy. Shown in Fig.1. It is radiant light and heat from the sun that is a natural source of energy using a range of ever changing and developing technologies such as solar thermal energy, solar architecture, solar heating, molten salt power plant and artificial photosynthesis. The large magnitude of solar power available makes a highly appealing source of electricity. 30% (approx.) solar radiation is back to space while the rest is absorbed by ocean, clouds and land masses.



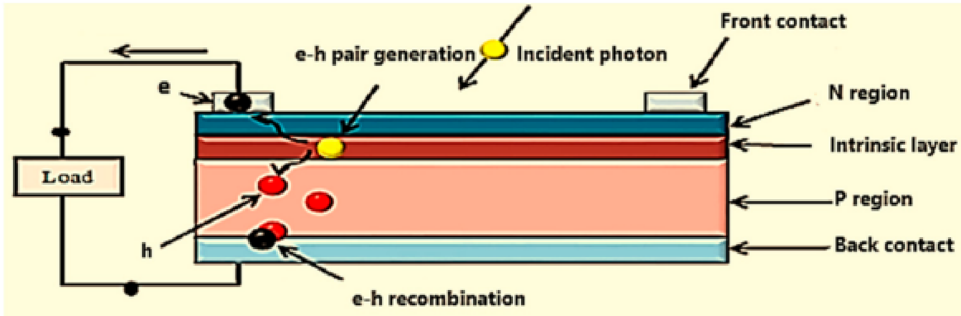
[4]

Figure 1.3: Internal of Reaction of Solar energy

Working of Solar PV

A photovoltaic system operates to generate electricity and the operation is similar for both the off-grid and on-grid photovoltaic systems. Whenever the incident light energy on the photovoltaic module is enough to produce electrons, then DC power is generated at the output terminals of the PV array and then is fed to the power converters which in turn helps in DC to AC conversion. The AC energy can be used directly to electrical loads, or it can be supplied to the utility grid by means of a net metering facility. If the generated is utilized for various load applications at the generation level itself, then it is said to be a standalone PV system, if the generated energy is continuously fed to the utility grid then it can be termed as on-grid photovoltaic system **[3]**.

A PV cell is the essential unit of a solar energy generation system in which sunlight is promptly converted to electrical energy. The solar cell is a p-n junction device. n-type refers to the negatively charged electrons donated by donor impurity atoms and p-type refers to the positively charged holes created by acceptor impurity atoms.



[4]

Figure 1.4: A p-n junction PV cell

Components of Solar PV

1. Solar Cell Panels

Solar panels are multiple solar cells connected in series and parallel to produce a certain power output. One PV cell is unfeasible for most applications as it can only produce about 0.5 V. For example, six cells are connected in series, the cell is assumed to have the same current as a single cell and ideal 3 V (6 × 0.5 V). Series cells are also connected in parallel for higher current capacity. If the six cells can generate 2 A, the series-parallel structure of twelve cells is supposed to generate 4 A and 3 V. **[5]**

2. Junction Box

The junction boxes were used majorly in two different places in PV systems i.e. one is at the interconnection to power converter. Here all the PV strings are joined together. Another place is at a solar PV enclosure where this junction is used comprises the bypass diodes allowing the power flow only in one direction i.e. from the solar panel to the utility system.

3. On-Grid Inverter

On-grid inverter is the one which converts the DC power to AC power. This is one of the essential components of a PV system to interconnect with the present day power sector. We have various types of inverters available in the market whose rating is from small kVA to larger kVA. The present available inverters are coming with MPPT enabled and wider input Vdc range.

4. **AC disconnect & Main Panel**

In photovoltaic systems DC and AC disconnect are the two boxes where AC disconnect's role is to separate the on-grid power converter i.e. DC-AC inverter from the electrical utility grid. Output currents of the inverters have to be taken into consideration while sizing the AC disconnect and it simply be a circuit breaker. This is generally placed in the Main panel.

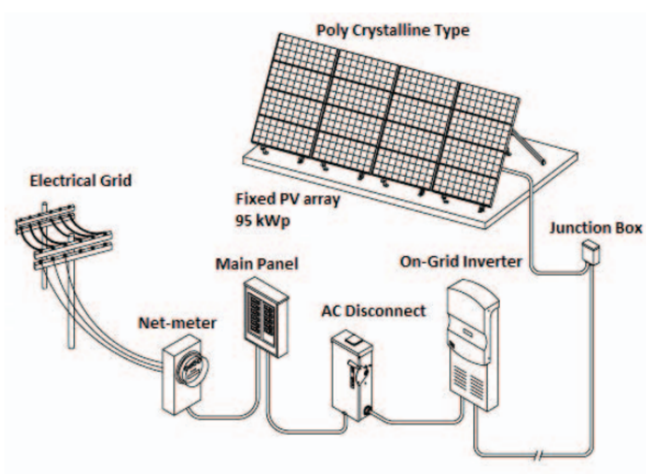
Main panel comes into picture before the electrical system can be integrated into the electrical power grid. This generally consists of electro mechanical devices that are used to disconnect the photovoltaic system from the electric grid.

5. **Net Meter**

Net meter is a device that is used to monitor the inflow and outflow of electricity between the electrical power generating system and the electric utility grid. In photovoltaic systems if excess energy is generated that can be sold to the utility by means of this.

6. **Electrical Grid**

It is an electrical power network interconnecting the load centers and energy providers. It is one of the major parts of the electrical power system network acting as the interface between power generation plant, power transmission line, and distribution lines. It transmits electric power that is generated using any source (renewable or nonrenewable) at a any place and distributes finally to the consumers as per the requirement (either in 1-ɮ or/and in 3-ɮ).



[6]

Figure 1.5: Schematic view of on-grid photovoltaic system

Auxiliary components of Solar PV

1. **Monitoring systems**

The main purposes of a monitoring system are to follow up on the energy yield, to assess the PV system performance and to timely identify design flaws or malfunctions. Many large PV systems use analytical monitoring to prevent economic losses due to operational problems.

In the case of utility scale PV plants, monitoring typically serves for comparison of the current plant performance with an initial energy yield assessment. In order to be able to distinguish the performance of the PV system from the variability of the solar resource, monitoring should always include both a measurement of the energy generated and the incoming irradiation. **[7]**

2. **Datalogger**

Grid-connected PV systems usually have high budgets, and the associated data acquisition devices, commonly known as data loggers, allow to measure the main parameters to carry out the necessary corrective and maintenance actions without a high impact on the total installation cost.

The data logger uses a data acquisition card installed in a PC with 16 single ended or eight differential analog, an ADC converter with a 12-bit accuracy, 8 digital input/output channels and 2 up/down timer/counters. **[8]**

3. **Pyranometers**

Thermopile pyranometers are the standard solar measuring instrument for monitoring weather conditions and any research requiring a high degree of accuracy. They are occasionally used for evaluating the efficiency of a photovoltaic system, though photovoltaic pyranometers based on silicon cells are more suitable.

1.2 Types of PV panels

The three types of PV panels used in this experimental study are :

1. Bifacial PV module
2. half cut PV module

1. Bifacial PV module

Bifacial modules provide a unique property of being able to absorb radiation from front as well as module rear which implies that bifacial modules will generate more energy on a given day at a given location. Extra energy due to bifacial characteristics allows for cost and area savings, as high energy density in case of bifacial modules correlates to enhanced energy for the same area. This further implies lower levelized cost of energy (LCOE) [1,2]. Consequently, bifacial modules also present an opportunity of increased savings and subsequent reduction in payback time.

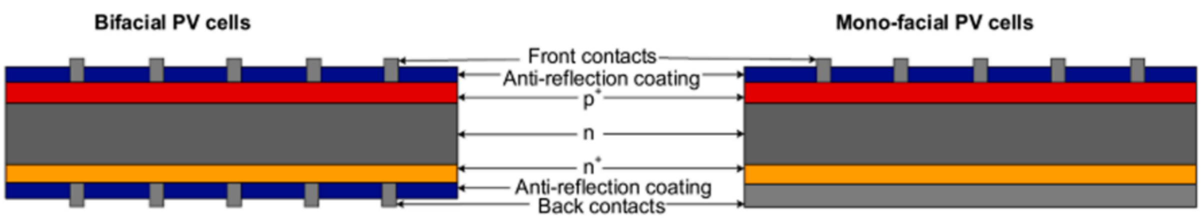
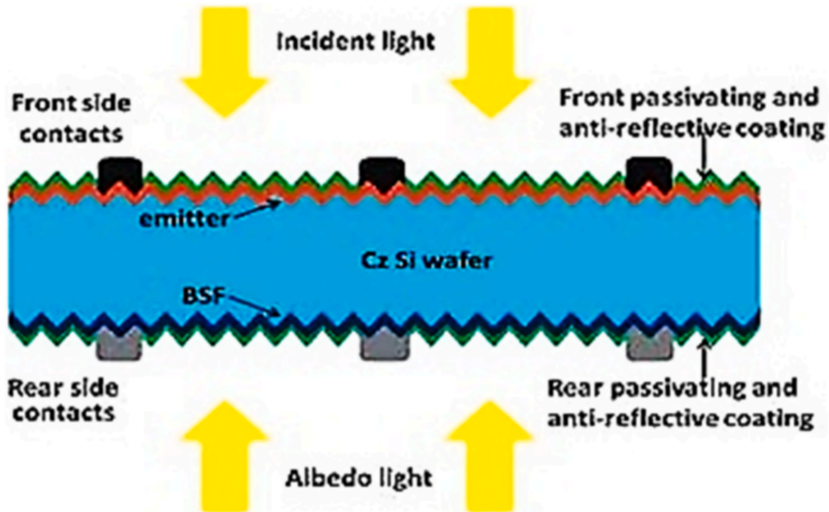


Figure 1.6: Bifacial vs Monofacial PV cell

A fundamental physical distinction between a bifacial solar cell and a monofacial type cell is the technique of passivation of the electrode over the rear part of the cell. For monofacial cells, the rear electrode is overlaid as a distinct layer while in case of a bifacial cell, the contacts on the rear are contrived in the shape of a metallic grid .

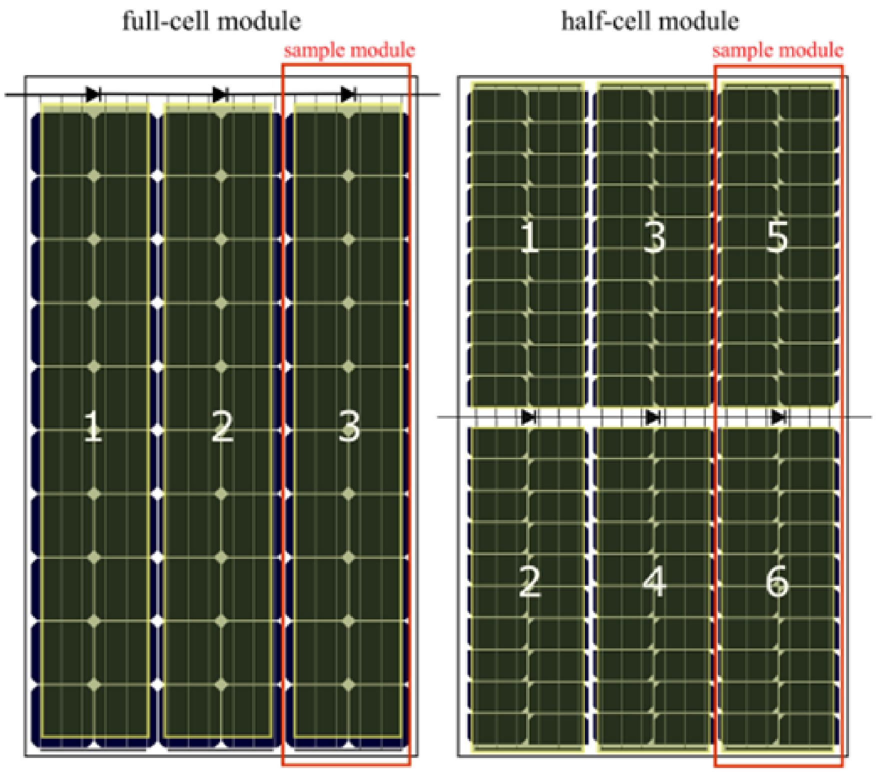


[9]

Figure 1.7: Cross-Section of a Bifacial Solar Cell

2. half cut PV module

PV modules using half-cut solar cells are reported to have reduced cell-tomodule energy yield loss through lower series resistance loss and enhanced optical yield [2], [3]. Recently, half-cut p-type Cz silicon solar cells have exceeded 22% efficiency in mass production [4]. The market share of half-cell modules is expected to grow from 5% in 2018 to 40% in 2028 [1].Half-cell modules are reported to have different shading responses, namely the hotspots effect compared with the conventional fuel-cell modules [8], [9]. The hotspot effect occurs when the maximum current generation capacity of one or more cells in a series-connected solar cell string is reduced to values lower than the operating current of the module, often depending on the external circuit.



[11]

Figure 1.8: Standard 60-full-cell module and 120-half-cell module configurations with three bypass diodes

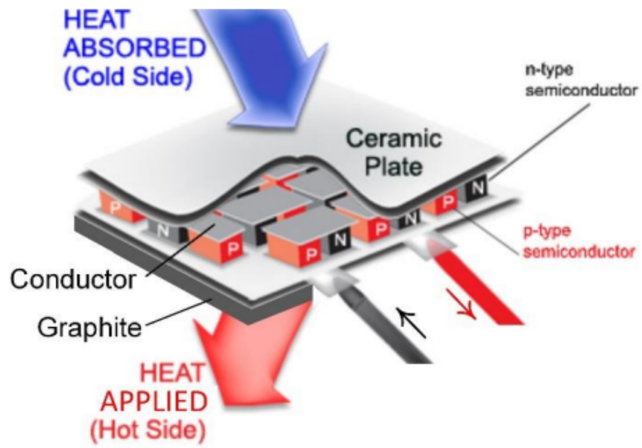
1.3 Types of irradiation sensors

The two types of irradiation sensors used in this experimental study are :

1. Thermopile pyranometer
2. Reference cell (Photovoltaic pyranometer)

1. Thermopile pyranometer

The heart of the pyranometer is a thermopile which is based on several thermocouples connected in series and in parallel by two junctions. This kind of device uses the Peltier effect which represents the most appropriate choice to our conception of a solar radiation detection cell. Peltier device is a solid-state active heat pump which transfers heat from one side of the device to the other, with consumption of electrical energy that depends on the direction of the current. It creates a heat flux between the junctions of two different types of materials [7]. In our context, the device is used as a sensor (self-generating sensor) and not as an actuator. Thus, the operating principle is that once the radiation of the sun is going to strike the part which is in front of the hot junction and consequently leading to a rise of temperature. In parallel the part which is shielded from the sun (cold junction) stays in the ambient temperature. This temperature gradient created between the two sides of the device results in a voltage difference output proportional to the rate of the receiving radiation as defined from Seebeck effect.

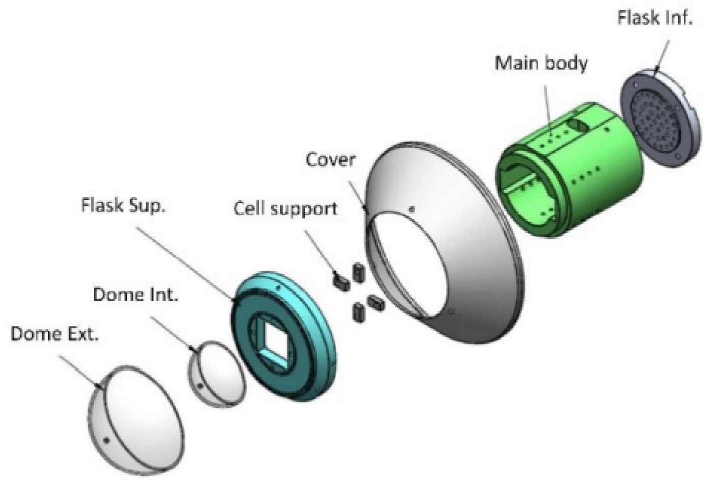


[12]

Figure 1.9: Representation of the Peltier module with Seebeck effect including graphite on its hot side**.**

Mechanical structure

The construction is structured in three parts. The first part contains the glass domes with the Peltier device, the second part is the pyranometer body which contains the PCB electronics circuit and the third part serves to protect the pyranometer from the rays of sunshine and also to avoid the increasing heat.



[13]

Figure 1.10: Design parts of the solar Pyranomete

[14]

Figure 1.11: PYR1-485 THERMOPILE PYRANOMETER

2. Reference cell (Photovoltaic pyranometer)

Reference cells are widely used in the photovoltaic (PV) industry to measure irradiance. For field applications and outdoor use a variety of products are on the market and they are often perceived as low-cost alternatives to thermopile pyranometers. **[15]**

PV reference cells can also be used to measure irradiance. However, they work in a very different way: photons with energy above the band gap of the PV material are converted directly into positive and negative charges that can be collected and used in an external circuit. The reference cell generates a current that is dependent on the number and spectral distribution of the photons. Typically, the current of the reference cell is measured by measuring the voltage across a small resistor that is included in the reference cell package.

If a solar reference cell is constructed with typical PV cells, glass, encapsulant, and backsheet the spectral and angular response will closely match that of the PV modules generating energy in the power plant. The reference cell does not respond to photons with energy less than the band gap, implying that they will be insensitive to changes in this part of the spectrum when used for quantifying the broadband meteorological irradiance. Or, in other words, **a reference cell is designed to measure the irradiance that is available to a PV module for conversion into electricity (fuel in) rather than being designed to measure the broadband irradiance.** The close spectral match of the reference cell to a PV system minimizes scatter in the data due to variable spectral conditions. The attributes that introduce uncertainty when reference cells are used to characterize the weather are the same as the attributes that make them more ideal for characterizing the PV system performance. **[16]**

[17]

Figure 1.12: SUNMETER PRO – ACCURATE, RELIABLE PHOTOVOLTAIC PYRANOMETER

2
System Description

The main purpose of the study is to study the different types of PV module systems ie; Bifacial PV module and half-cut PV module, the experimental setup is specifically built up for this setup.

The experimental setup is made up of:-

- Two Bifacial PV modules - **LG NeON® 2 BiFacial**
  Maximum production capacity - 335 Wh @ STC

STC (Standard Test Conditions): Irradiance 1000 W/m2, module temperature 25 °C, AM 1,5.

- Two half cut PV modules - **Futura Sun MODULO SILK® PRO**
  Maximum production capacity - 360 W @ STC

STC (Standard Test Conditions): Irradiance 1000 W/m2- AM 1,5 - 25 °C

- Micro Inverters for each PV module - **Enphase IQ 7A Microinverter**
  Peak output power 366 VA @ 240 VAC and 295 VA @ 208 VAC

- One wattmeter for each type of PV module which sums up to total of two wattmeters for the entire setup - **EED QI-POWER-485-LV**
  Current: Up to 50 A AC/DC
  Voltage: up to 80 V AC or 100V DC

- Two Photovoltaic Pyranometers and Two Thermopile Pyranometers for Bifacial PV module for measuring direct and reflected sun rays.

  Photovoltaic Pyranometer - **Soluzione Solare SUNMETER PRO**

  Irradiance range: 0 ÷ 1500 W/m2 temperature compensated

  Thermopile Pyranometer **- Soluzione Solare PYRANOMETER PYRA-485**

  Input irradiance range: 0 ÷ 1600 W/m2

- One Photovoltaic Pyranometer and One Thermopile Pyranometer for half cut Pyranometer,
- Main power switch to control the power flow for the entire setup,
- Dedicated power switch to each pair of PV module to control to power flow,
- Datahub box for serving as junction for all the data output and delivering it to the data logger

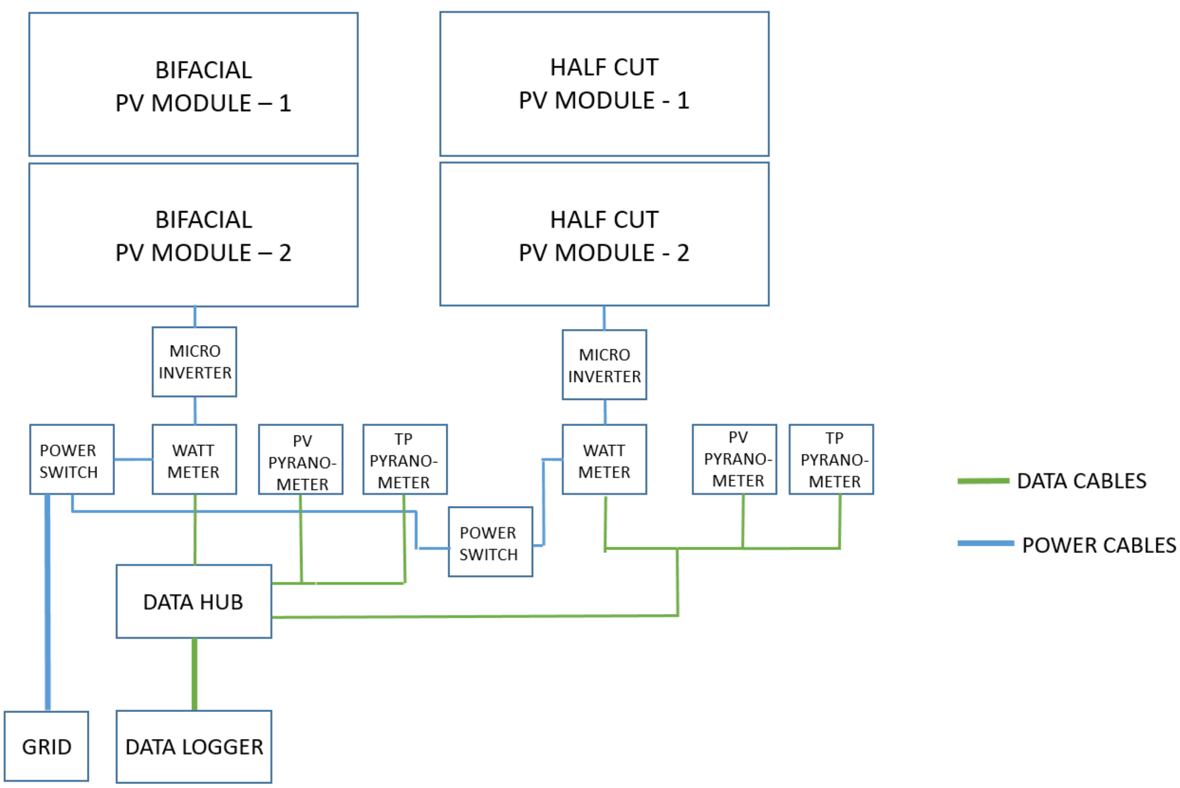


Figure 2.1 : Power and Data connections diagram

Figure 2.2 : Front view of the experimental setup with bifacial PV module on left and halfcut PV module on right

Figure 2.3 : Rear view of the experimental setup with the halfcut PV module

Figure 2.4 : Rear view of the experimental setup with the bifacial PV module

Figure 2.5 : Side view of the experimental setup with bifacial PV module and halfcut PV module

2.1 Data Acquisition system

In this experimental setup, in order to measure the irradiance values in W/m2 two types of pyranometers namely Thermopile pyranometer (PYRA-485) and Photovoltaic pyranometer (SUNMETER PRO) produced by Soluzione Solare S.r.l were used . For measuring the energy produced in measure using Wattmeter. All the devices uses the MODBUS 485 protocol for communication.

Figure 2.6 : Side view of the experimental setup with bifacial PV module and halfcut PV module with photovoltaic pyranometer attached to it

Figure 2.7 : Sunmeter Pro - Photovoltaic pyranometer produced by Soluzione Solare S.r.l

Inputs:	
irradiance range:	0 ÷ 1500 W/m^2 temperature compensated
temperature range:	-30 ÷ +90 °C measurable with external PT100 RTD
digital:	PNP-like connection
Outputs:	
analog:	configurable as voltage (0 ÷ 10 V / 0 ÷ 5 V) or current (0 ÷ 20 mA / 4 ÷ 20 mA)
serial:	RS485, standard Modbus RTU protocol
Measurements precision:	
irradiance:	< ± 2%
temperature:	< ± 0.5 °C
Supply:	9 ÷ 30 Vdc, protected against reverse polarity
Encapsulation:	small microprismatic glass for photovoltaic modules and E.V.A
Case:	anodized aluminium with stainless steel screw-clamp to fix it on modules or montage profile
Wiring:	50 cm cable, UV resistant
Connectors:	male M12 8 pin circular, IP67 code, UV resistant, matching female supplied
	female M8 3 pin circular IP67
Dimensions:	114 x 70 x 22 mm, with mounting bracket 128 x 70 x 65 mm (overall)
Operating temperature:	-20°C ÷ +80 °C (transport and storage -35°C ÷ +95 °C)

Table 2.1 : Specifications table of Sunmeter Pro photovoltaic pyranometer

Figure 2.8 : PYR1-485 - Thermopile pyranometer produced by Soluzione Solare S.r.l

	PYR1-485	PYR2-485
Measurements:		
spectral range:	300 ÷ 2900nm	
input irradiance range:	0 ÷ 1600 W/m^2	
Response time:	< 20 sec	<25 sec
Temperature response:	< ± 2 % (-10 to +40°C)	< ± 5 % (-10 to +40°C)
Zero offset		
Thermal radiation (at 200 W/m^2)	<14 W/m^2	<20 W/m^2
Temperature change (5 k/h)	<± 3	<± 6 W/m^2
Resolution		
Smallest detectable change	Irradinace: ± 1 W/m^2	
	Inclination: 0.1°	
Outputs		
serial:	RS485, standard Modbus RTU protocol	
Output resolution:	1 W/m^2	
Output precision:		
Tilt response (0 ÷ 90°):	< ± 2%	< ± 4%
Temp. Response (Δt = 50K)	< 4%	< 8%
Working temperature:	-40 ÷ +80 °C	
Supply:	9 ÷ 30 Vdc protected against short circuit	
Encapsulation:	Quartz [k5]	
	Double glass dome	Single glass dome
Special glass transparent to:	0,3 ÷ 3,0 µm	0,3 ÷ 3,0 µm
Case:	Anodized aluminum	
Connectors:	standard M8 4 pin female	
Dimensions:	Φ 162 x h 104 mm	

Table 2.2 : Specifications table of PYR1-485 Thermopile pyranometer pyranometer

The energy produced was measured using Wattmeter (QI-POWER-485) produced by EED.

Figure 2.9 : QI Power 485 wattmeter produced by QEED

POWER SUPPLY	9...30 Vdc, protection against polarity reversal and overtemperature.
ABSORPTION	< 1,3 W
MEASUREMENT	Irms, Vrms, Watt, Var, Va, Vpk, Ipk,Frequency, Cosφ, Energy bidirectional, THD, min e MAX of each measure
TYPE OF MEASURE	**TRMS or DC**
RANGE	**Current: up to 50 A AC/DC** **Voltage: up to 80 VAC or 100 VDC**
ACCURACY	@25 °C up to 200 Hz Voltage, Current, Active Power: **< 0,5% F.S.** Frequency: **± 0,1 Hz** Energy: **± 1% of reading** Vpeak, Ipeak: **± 5% F.S.**
OUTPUT	**RS485 Modbus RTU**
BAUDRATE	From 1.200 a 115.200 baud
CREST FACTOR	1,8 (on current measurement)
WORKING FREQUENCY	DC or 1...400 Hz
SAMPLING RATE	11k samples per second
INPUT IMPEDENCE	1 Mohm ± 1%
STANDARDS CE	EN61000-6-4/2006 + A1 2011; EN64000-6-2/2005; EN61010-1/2010
OVERVOLTAGE CATEGORY	Cat IV up to 100 V
INSULATION	3 kV on bare wire for Current measure. 4 kV for Voltage measure (reinforced insulation to power supply and serial output)
PROTECTION INDEX	IP20
TEMPERATURE COEFFICIENT	< 200 ppm/°C
WORKING TEMPERATURE	-15...+65°C
STORAGE TEMPERATURE	-40°C... +85°C
HUMIDITY	10...90% not condensing
ALTITUDE	Up to 2000 m s.l.m.
DIMENSIONS	46,1 x 63 x 26,4 mm (terminal excluded)
TERMINALS	Removable terminals 3,5 mm, n°1 of 4 poles, n°2 of 2 poles
WEIGHT	80 g

Table 2.3 : Specifications of QI Power 485 wattmeter

From the both Irradiance sensor and Wattmeter the data is transferred using MODBUS RS485 protocol to the Datalogger M502 produced by GH solutions s.r.l. Data acquisition time was set as every 1 minute from the Datalogger.

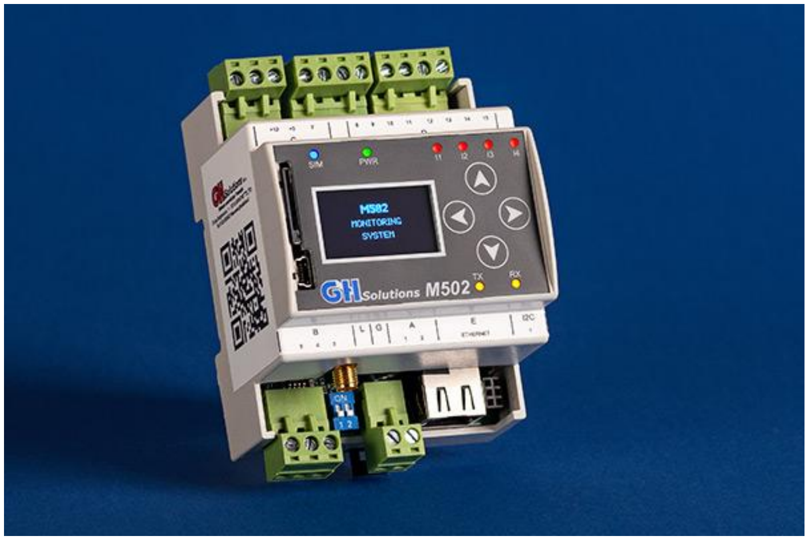


Figure 2.10 : Datalogger M502 produced by GH solutions s.r.l.

Supply voltage:.	12-24 VAC o VDC
Frequency in AC:	ZH 09 / ZH 09
Work temperatures:	+ 50 -10 degrees centigrade
Absorption:.	300 has max
Container:	Din 4 modules type
Dimensions and dimensions:	Without terminal blocks = 72 x 90 x 62 mm
	With terminal blocks = 72 x 110 x 62 mm
Weight (without antenna, sim and SD):	240 g
Impulse frequency:	Setable from 1 to 255 ms
MoTERIERE:	Vite removable for conductors with sec. maximum of 1.5 mm
Antenna:	Standard SMA male screw connector
USB:	"B" type connector Mini
Ethernet:	RJ45

Table 2.4 : Specifications of Datalogger M502

3

Experimental Setup

3.1 Geographical Location of the experimental setup

Soluzione Solare S.r.l.
Via Riviera Berica 621 - 36100
Vicenza (VI)

Location coordinates - 45.506837928613955, 11.569860117972507

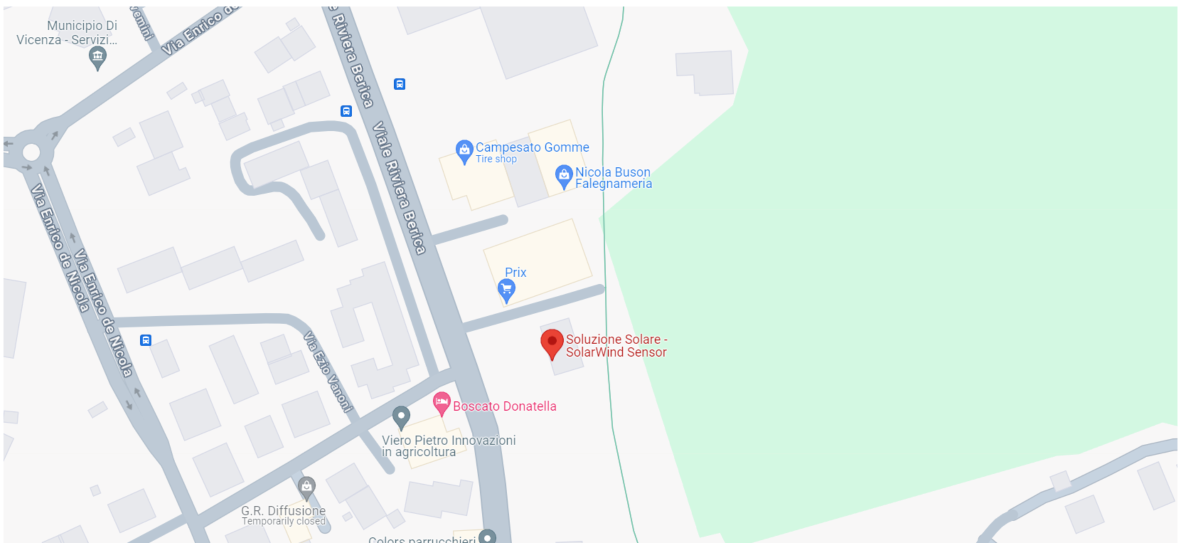


Figure 3.1 : Geographical location of the experimental setup in the map

3.2 PV panel mounting and setup

For this experiment the two quantities of PV modules for each type were used in order to increase the accuracy and reliability of the data. PV modules were mounted on an aluminum frame in order to avoid corrosion due to environmental factors like humidity and rain.

PV modules are attached to the aluminum structure using a hinge on one side and free on the other side, which makes the PV modules act like a flap and so the structure is not affected during heavy winds.

Wheels have been attached to the bottom of structure in order to support easy movement of the structure incase required to relocate. Height from the ground and Angle of inclination was chosen for optimal power production.

For Bifacial PV modules green grass floor has higher bifacial spectral benefit, which leads to higher yields.

https://www.sciencedirect.com/science/article/abs/pii/S0038092X2200768X#:~:text=Green%20grass%20is%20found%20to,of%20bifacial%20spectral%20energy%20gains.

Bi facial PV panel structure characteristics

Height = 169 cm
Width = 170 cm
Angle of inclination = 32 degrees

Half cut PV panel structure characteristics

Height = 168 cm
Width = 180 cm
Angle of inclination = 31 degrees

At the back of each aluminum frame structure, a rectangular sheet made of stainless steel was attached in order to accommodate the sensors and power control devices.

Figure 3.2 : Side view of the experimental setup

3.3 Irradiance sensor mounting and setup

As mentioned before, we are using 2 types of irradiance sensor in the experimental study which are Photovoltaic Pyranometer and Thermopile pyranometer.

The Pyranometers are mounted using clamps on the PV module structure at the same plane and angle as the PV modules in order to receive and measure the same amount of irradiance from the sun.

In Bi facial PV module at an angle of 32 degrees
In Half cut PV module at an angle of 31 degrees

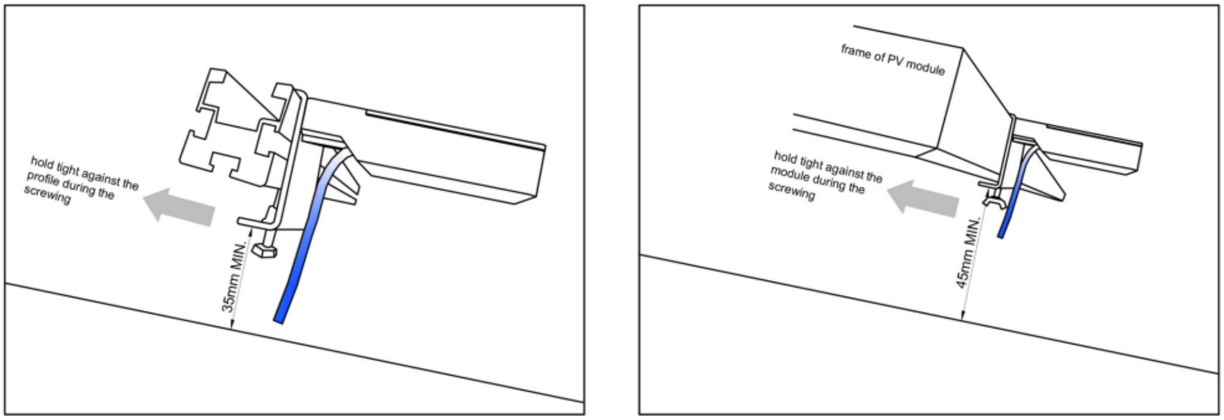


Figure 3.3 : Mounting of Sunmeter Pro PV pyranometer

https://soluzionesolare.com/products/sunmeter-pro-photovoltaic-pyranometer/

For the Bifacial PV module, both the Photovoltaic Pyranometer and Thermopile pyranometer were mounted also facing the ground side in order to measure the irradiation values of reflected rays of the sun.

Figure 3.4 : Mounting of Sunmeter Pro photovoltaic pyranometer

3.4 Micro Inverter mounting and setup

The purpose of the micro inverter is to convert the DC power produced by the PV module into AC power which is the type of power which is transferred in the power grid.

Instead of using a one inverter for all the PV modules together, for each PV module a dedicated Micro Inverter was used in order to accurately measure the power produced by each PV module for having more reliable data.
Microinverters were mounted below the PV panels in order to protect them from being directly exposed to humidity and rain. It also keeps them safe from other external factors.

The power outputs from the PV panels are connected to the Micro Inverter and then the AC power output is sent to the wattmeter.

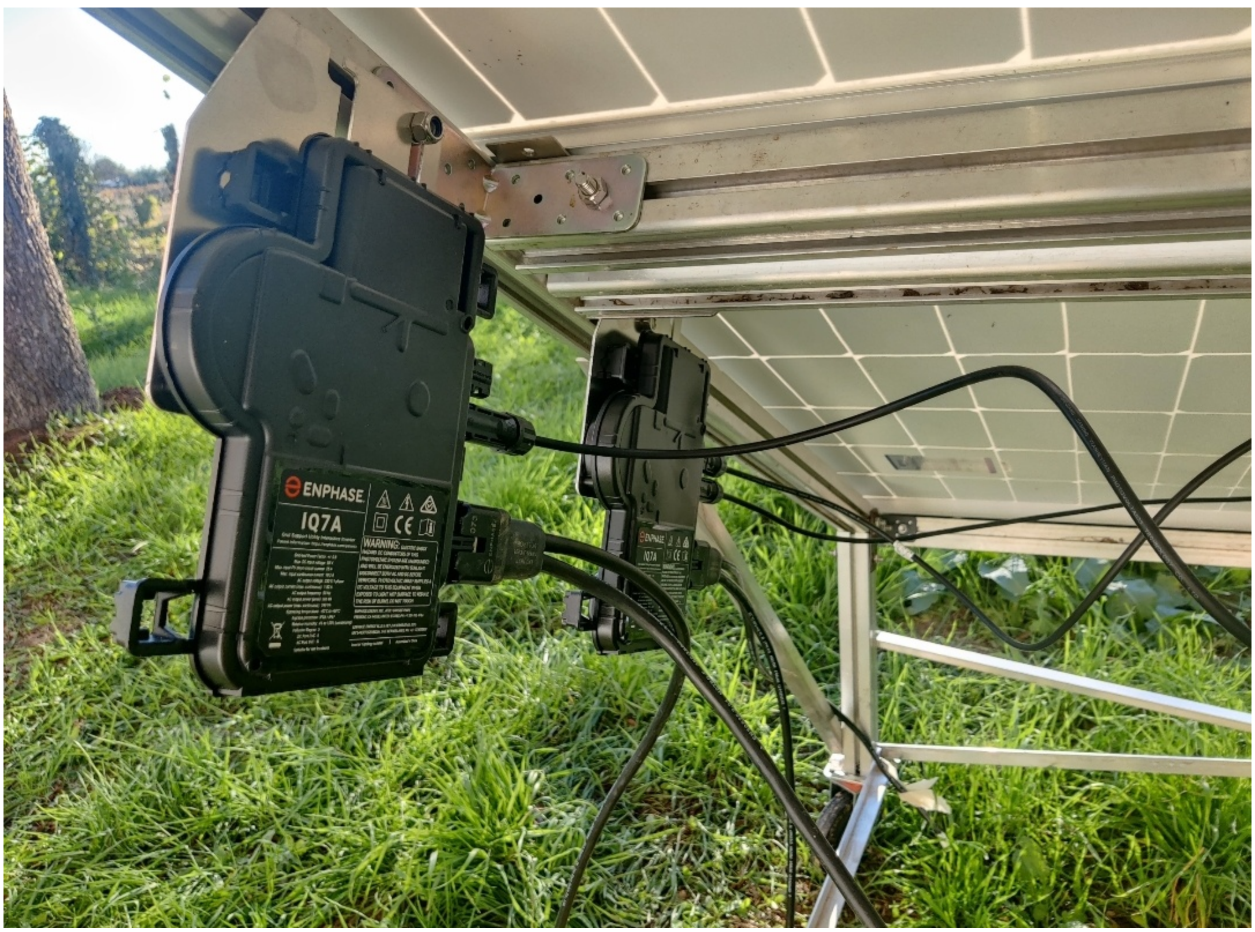


Figure 3.5 : Microinverter mounted under the half cut PV module structure

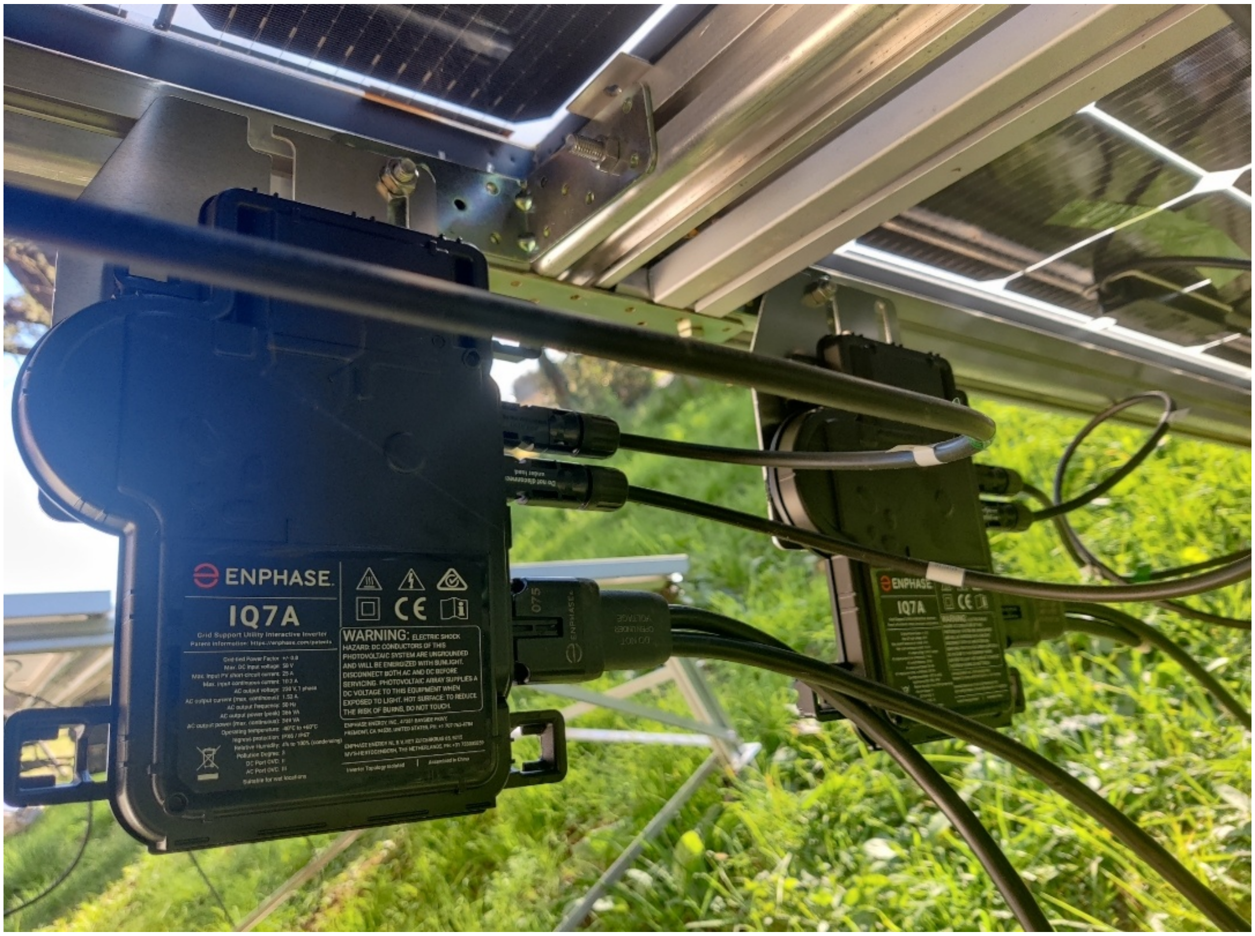


Figure 3.6 : Microinverter mounted under the bifacial PV module structure

3.5 Wattmeter mounting and setup

For this study, in order to measure the Max W produced by each type of PV modules. This value gives the actual amount of power produced. A dedicated wattmeter for each type PV module for measuring the power produced separately which helps to make a comparison.

The wattmeter is placed inside an IP65 water resistant electric box and mounted on a stainless steel sheet which is fixed on the back of the PV module. It is placed at the back of the PV module in order to avoid direct exposure to environmental factors like humidity and rain.

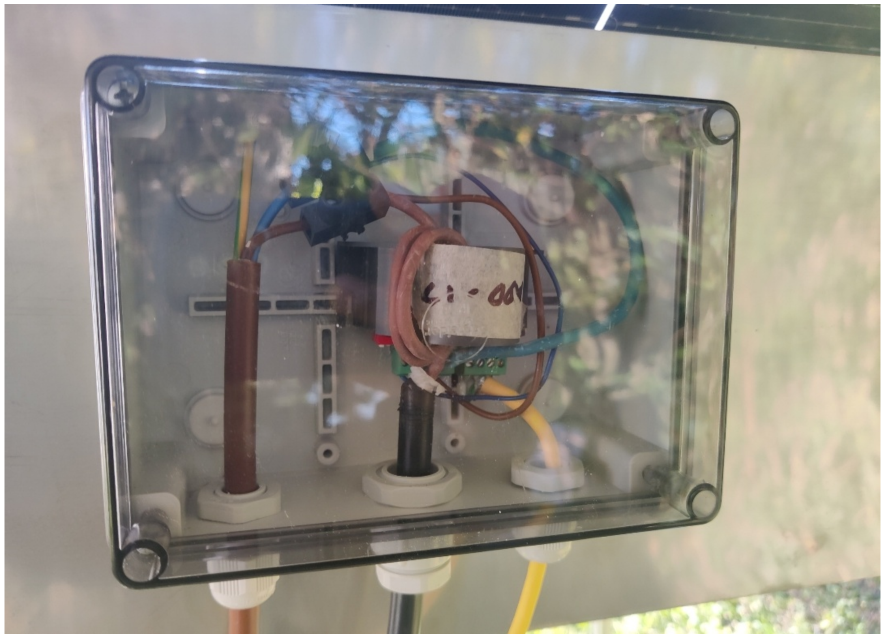


Figure 3.7 : Wattmeter mounted on the back of half cut PV module structure

3.6 Data hub mounting and setup

In this study, the purpose of the Data hub is to collect all the MODBUS RS485 data cables coming from different sensors in a single place and transfer it to the Datalogger through a single wire in order to read all the input data from the different sensors.

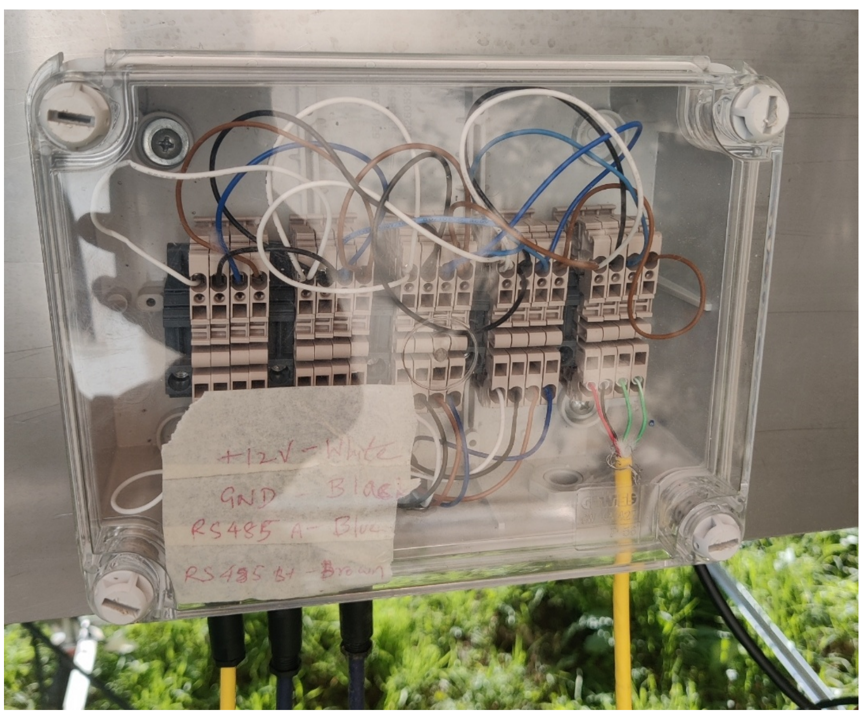


Figure 3.8 : Wattmeter mounted on the back of half cut PV module structure

Similar to the Wattmeter the Datahub is placed inside an IP65 water resistant electric box and mounted on a stainless steel sheet which is fixed on the back of the PV module. It is placed at the back of the PV module in order to avoid direct exposure to environmental factors like humidity and rain.

3.7 Power switches mounting and setup

In order to control the power, each PV module is provided with a power switch of 16 Amperes each. The switches are placed inside an IP65 water-resistant electric box and mounted on a stainless steel sheet which is fixed on the back of the PV module. It is placed at the back of the PV module in order to avoid direct exposure to environmental factors like humidity and rain.

Additionally, a main power switch is also provided which can control the power supply from both the PV modules in order to have full control over the power circuit.

Figure 3.9 : Main power switch mounted on the back of half cut PV module structure

Figure 3.10 : Dedicated power switch mounted on the back of bifacial cut PV module structure

3.8 Data logger - Channels and Addresses

Datalogger is a device which is used to read, collect and visualize the output data in one single place from all the sensors which are used in this experimental setup. The data logger uses a MODBUS RS485 protocol to communicate with all the devices within the setup.

The MODBUS RS485 protocol parameters used in this setup are given below ,

Bitrate - 19200
Data bits - 8
Parity bit - None
Stop bit - 1

Using the dedicated software called ‘Picolink’ by the GH solutions s.r.l who is producer of the Datalogger M502, each channel has been dedicated for each sensor connected in this whole setup. Appropriate description and Unit of Measurement has been set for each sensor. This helps to read the values of each sensor without any issue.

The channel numbers and description of each sensor are represented in the image below.

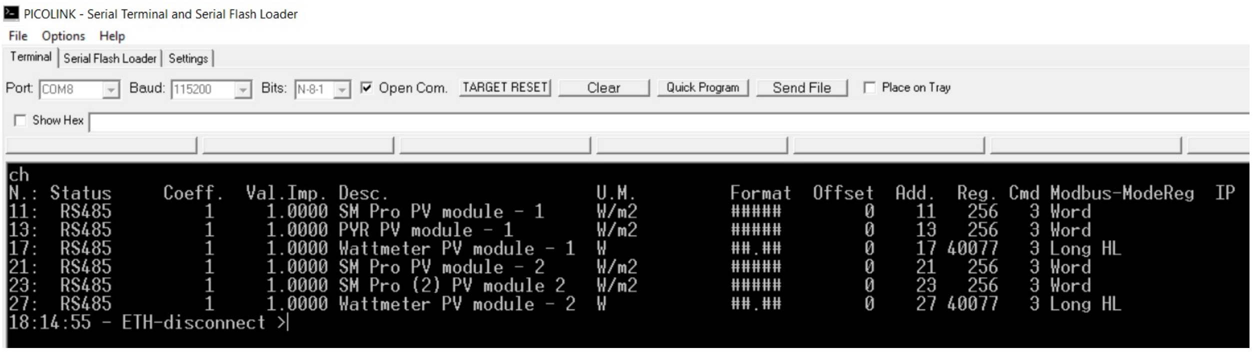


Figure 3.11 : List of channels with configuration in datalogger M502

Figure 3.12 : Datalogger M502 produced by GH solutions S.r.l

3.9 Data collection and transfer

The Datalogger M502 uses the ethernet for transferring data files. The data collected from the data logger can be received every few mins set in the format of excel .csv (Comma Separated Values) file.

In the experiment the data acquisition time has been set as every one minute.

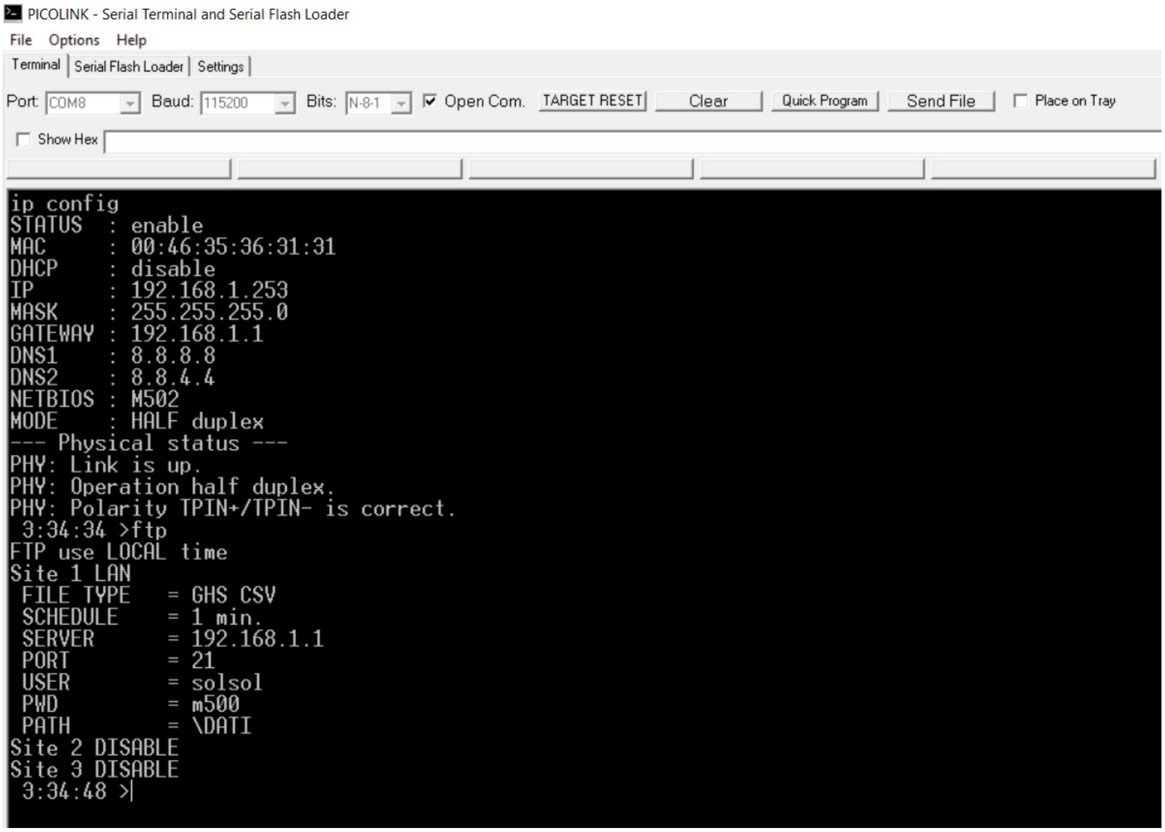


Figure 3.13 : Picolink - terminal for configuring Datalogger M502 produced by GH solutions S.r.l

4

Experimental Test Description

In this experiment, we study the comparison between two types of PV modules namely Bifacial PV module and Half cut PV module. Also in this study the comparison between the two types of pyranometers namely Photovoltaic pyranometer and Thermopile pyranometer are also made. Data from clear and sunny days were chosen for better results in comparisons made.

The parameters measured during this experiment are irradiation values measured by the two types of pyranometers and comparing it with the actual Energy production from the PV modules using Wattmeter.

Secondly, the Energy production values of both the types of PV modules at the same time for comparing the energy production efficiency of each type of PV module.

The theoretical Energy produced by the PV module is calculated using the irradiance value measured by the irradiance sensor and dividing it with the PV coefficient value.

Theoretical Energy produced = Hourly Irradiance measured /PV Coefficient

PV coefficient is calculated using the formula below,

PV coefficient = STC Irradiance value / STC Energy produced * Number of PV modules

PV coefficient for Bifacial PV module = 1000/380*2 = 1.31

PV coefficient for Half cut PV module = 1000/360*2 = 1.38

These coefficient values will be used in the experimental tests of this study.

5

Experimental Data Results

5.1 Test day 1

The test results of Day 1 (17/11/2023) are given below

For Bifacial PV module

Time of the day	Irradiation in PV pyranometer (W/m^2/h)	Irradiation in PV pyranometer-Bifacial (W/m^2/h)	Theoretical Energy calculated using PV Pyranometer (Wh)	Actual Energy measured in Wattmeter (Wh)
09:00 AM	325.24	30.55	271.60	257.57
10:00 AM	504.07	39.8	415.17	401.26
11:00 AM	764.84	52.13	623.64	609.67
12:00 PM	744.01	50.44	606.45	587.94
01:00 PM	616.54	42.43	503.03	484.89
02:00 PM	272.75	20.1	223.55	211.44

Table 5.1 Experimental data results of Bifacial PV on test day 1

Total Theoretical Energy Measured by the PV Pyranometer in the day (6 hours) = 2,643.44 Wh

Total Actual Energy Measured by the Wattmeter in the day (6 hours) = 2552.77 Wh

Percentage deviation between Total Theoretical Energy measured by PV Pyranometer and Total Actual Energy Measured by the Wattmeter = 0.91%

For Halfcut PV module

Time of the day	Irradiation in PV pyranometer (W/m^2/h)	Irradiation in Thermopile Pyranometer (W/m^2/h)	Theoretical Energy calculated using PV Pyranometer	Theoretical Energy calculated using Thermopile Pyranometer (Wh)	Actual Energy measured in Wattmeter (Wh)
09:00 AM	380.84	340	275.97	246.38	267.57
10:00 AM	537.68	501.21	389.62	363.20	376.26
11:00 AM	720.8	684.93	522.32	496.33	514.67
12:00 PM	755.6	703.71	547.54	509.93	532.94
01:00 PM	646.88	576.68	468.75	417.88	446.89
02:00 PM	383.21	320.88	277.69	232.52	259.44

Table 5.2 Experimental data results of half PV on test day 1

Total Theoretical Energy Measured by the PV Pyranometer in the day (6 hours) = 2,481.89 Wh

Total Theoretical Energy Measured by the Thermopile Pyranometer in the day (6 hours) = 2,266.24 Wh

Total Actual Energy Measured by the Wattmeter in the day (6 hours) = 2397.77 Wh

Percentage deviation between Total Theoretical Energy measured by PV Pyranometer and Total Actual Energy Measured by the Wattmeter = -0.84%

Percentage deviation between Total Theoretical Energy measured by Thermopile Pyranometer and Total Actual Energy Measured by the Wattmeter = 1.32%

5.2 Test day 2

The test results of Day 2 (18/11/2023) are given below

For Bifacial PV module

Time of the day	Irradiation in PV pyranometer (W/m^2/h)	Irradiation in PV pyranometer-Bifacial (W/m^2/h)	Theoretical Energy calculated using PV Pyranometer (Wh)	Actual Energy measured in Wattmeter (Wh)
09:00 AM	318.35	26.07	262.92	253.38
10:00 AM	554.93	47.41	459.80	434.78
11:00 AM	734.39	68.96	613.24	596.42
12:00 PM	781.71	71.85	651.57	624.64
01:00 PM	624.96	46.36	512.46	498.56
02:00 PM	306.42	25.27	253.20	249.77

Table 5.3 Experimental data results of bifacial PV on test day 2

Total Theoretical Energy Measured by the PV Pyranometer in the day (6 hours) = 2,753.19 Wh

Total Actual Energy Measured by the Wattmeter in the day (6 hours) = 2657.55 Wh

Percentage deviation between Total Theoretical Energy measured by PV Pyranometer and Total Actual Energy Measured by the Wattmeter = 0.96%

For Halfcut PV module

Time of the day	Irradiation in PV pyranometer (W/m^2/h)	Irradiation in Thermopile Pyranometer (W/m^2/h)	Theoretical Energy calculated using PV Pyranometer	Theoretical Energy calculated using Thermopile Pyranometer	Actual Energy measured in Wattmeter (Wh)
09:00 AM	453.67	443.73	328.75	321.54	289.91
10:00 AM	551.85	539.46	399.89	390.91	411.10
11:00 AM	701.62	784.75	508.42	568.66	521.43
12:00 PM	879.68	903.14	637.45	654.45	657.94
01:00 PM	655.89	764.36	475.28	553.88	539.34
02:00 PM	433.54	503.51	314.16	364.86	310.11

Table 5.4 Experimental data results of half cut PV on test day 2

Total Theoretical Energy Measured by the PV Pyranometer in the day (6 hours) = 2663.95 W/m^2

Total Theoretical Energy Measured by the Thermopile Pyranometer in the day (6 hours) = 2854.31 W/m^2

Total Actual Energy Measured by the Wattmeter in the day (6 hours) = 2729.83 Wh

Percentage deviation between Total Theoretical Energy measured by PV Pyranometer and Total Actual Energy Measured by the Wattmeter = 0.66%

Percentage deviation between Total Theoretical Energy measured by Thermopile Pyranometer and Total Actual Energy Measured by the Wattmeter = -1.24%

5.3 Test day 3

The test results of Day 3 (19/11/2023) are given below

For Bifacial PV module

Time of the day	Irradiation in PV pyranometer (W/m^2/h)	Irradiation in PV pyranometer-Bifacial (W/m^2/h)	Theoretical Energy calculated using PV Pyranometer (Wh)	Actual Energy measured in Wattmeter (Wh)
09:00 AM	338.06	46.17	293.31	284.75
10:00 AM	529.71	58.81	449.25	434.82
11:00 AM	803.67	71.53	668.09	651.59
12:00 PM	759.36	66.94	630.76	602.09
01:00 PM	697.8	53.69	573.66	559.37
02:00 PM	262.42	34.7	226.81	202.44

Table 5.5 Experimental data results of bifacial PV on test day 3

Total Theoretical Energy Measured by the PV Pyranometer in the day (6 hours) = 2,841.88 Wh

Total Actual Energy Measured by the Wattmeter in the day (6 hours) = 2,735.06 Wh

Percentage deviation between Total Theoretical Energy measured by PV Pyranometer and Total Actual Energy Measured by the Wattmeter = 1.07%

For Halfcut PV module

Time of the day	Irradiation in PV pyranometer (W/m^2/h)	Irradiation in Thermopile Pyranometer (W/m^2/h)	Theoretical Energy calculated using PV Pyranometer	Theoretical Energy calculated using Thermopile Pyranometer	Actual Energy measured in Wattmeter (Wh)
09:00 AM	338.68	326.98	245.42	236.94	261.83
10:00 AM	456.51	408.60	330.80	296.09	370.48
11:00 AM	662.43	587.37	480.02	425.63	454.63
12:00 PM	714.59	628.82	517.82	455.67	455.35
01:00 PM	522.30	567.11	378.48	410.95	387.71
02:00 PM	303.71	271.42	220.08	196.68	218.64

Table 5.6 Experimental data results of halfcut PV on test day 3

Total Theoretical Energy Measured by the PV Pyranometer in the day (6 hours) = 2,172.62 Wh

Total Theoretical Energy Measured by the Thermopile Pyranometer in the day (6 hours) = 2,021.96 Wh

Total Actual Energy Measured by the Wattmeter in the day (6 hours) = 2148.64 Wh

Percentage deviation between Total Theoretical Energy measured by PV Pyranometer and Total Actual Energy Measured by the Wattmeter = -0.64%

Percentage deviation between Total Theoretical Energy measured by Thermopile Pyranometer and Total Actual Energy Measured by the Wattmeter =-1.13%

5.4 Test day 4

The test results of Day 4 (22/11/2023) are given below

For Bifacial PV module

Time of the day	Irradiation in PV pyranometer (W/m^2/h)	Irradiation in PV pyranometer-Bifacial (W/m^2/h)	Theoretical Energy calculated using PV Pyranometer	Actual Energy measured in Wattmeter (Wh)
09:00 AM	303.04	26.78	251.77	236.24
10:00 AM	472.52	31.46	384.72	353.9
11:00 AM	729.81	46.08	592.28	583.85
12:00 PM	737.3	58.91	607.79	597.02
01:00 PM	585.26	37.83	475.64	473.68
02:00 PM	291.37	31.24	246.27	243.33

Table 5.7 Experimental data results of bifacial PV on test day 4

Total Theoretical Energy Measured by the PV Pyranometer in the day (6 hours) = 2,558.47 W/m^2

Total Actual Energy Measured by the Wattmeter in the day (6 hours) = 2488.02 Wh

Percentage deviation between Total Theoretical Energy measured by PV Pyranometer and Total Actual Energy Measured by the Wattmeter = 0.70%

For Halfcut PV module

Time of the day	Irradiation in PV pyranometer (W/m^2/h)	Irradiation in Thermopile Pyranometer (W/m^2/h)	Theoretical Energy calculated using PV Pyranometer	Theoretical Energy calculated using Thermopile Pyranometer	Actual Energy measured in Wattmeter (Wh)
09:00 AM	371.91	393.48	268.84	284.78	269.68
10:00 AM	587.36	613.30	425.36	444.20	450.35
11:00 AM	807.85	865.09	584.78	626.81	547.83
12:00 PM	822.44	810.64	595.65	586.96	537.05
01:00 PM	658.7	707.36	476.81	512.32	509.62
02:00 PM	336.49	448.85	243.48	324.64	313.10

Table 5.8 Experimental data results of halfcutPV on test day 4

Total Theoretical Energy Measured by the PV Pyranometer in the day (6 hours) = 2,597.64 Wh

Total Theoretical Energy Measured by the Thermopile Pyranometer in the day (6 hours) = 2,781.68 Wh

Total Actual Energy Measured by the Wattmeter in the day (6 hours) = 2627.63 Wh

Percentage deviation between Total Theoretical Energy measured by PV Pyranometer and Total Actual Energy Measured by the Wattmeter = 0.30%

Percentage deviation between Total Theoretical Energy measured by Thermopile Pyranometer and Total Actual Energy Measured by the Wattmeter =-1.54%

5.5 Test day 5

The test results of Day 5 (23/11/2023) are given below

For Bifacial PV module

Time of the day	Irradiation in PV pyranometer (W/m^2/h)	Irradiation in PV pyranometer-Bifacial (W/m^2/h)	Theoretical Energy calculated using PV Pyranometer	Actual Energy measured in Wattmeter (Wh)
09:00 AM	347.93	35.94	293.03	279.52
10:00 AM	602.47	40.03	490.46	474.05
11:00 AM	738.38	59.48	609.05	653.47
12:00 PM	762.6	53.73	623.15	617.03
01:00 PM	725.74	44.81	588.21	552.4
02:00 PM	319.29	21.20	259.92	242.31

Table 5.9 Experimental data results of bifacial PV on test day 5

Total Theoretical Energy Measured by the PV Pyranometer in the day (6 hours) = 2,863.82 W/m^2

Total Actual Energy Measured by the Wattmeter in the day (6 hours) = 2818.78 Wh

Percentage deviation between Total Theoretical Energy measured by PV Pyranometer and Total Actual Energy Measured by the Wattmeter = 0.45%

For Halfcut PV module

Time of the day	Irradiation in PV pyranometer (W/m^2/h)	Irradiation in Thermopile Pyranometer (W/m^2/h)	Theoretical Energy calculated using PV Pyranometer	Theoretical Energy calculated using Thermopile Pyranometer	Actual Energy measured in Wattmeter (Wh)
09:00 AM	346.83	327.29	251.33	237.17	215.74
10:00 AM	495.57	500.72	359.11	362.84	369.49
11:00 AM	692.25	683.38	501.63	495.20	502.82
12:00 PM	642.69	621.63	465.72	450.46	486.04
01:00 PM	533.31	566.67	386.46	410.63	444.21
02:00 PM	321.09	296.29	232.67	214.70	208.90

Table 5.10 Experimental data results of halfcutPV on test day 5

Total Theoretical Energy Measured by the PV Pyranometer in the day (6 hours) = 2,196.91 Wh

Total Theoretical Energy Measured by the Thermopile Pyranometer in the day (6 hours) = 2,171.00 Wh

Total Actual Energy Measured by the Wattmeter in the day (6 hours) = 2227.20 Wh

Percentage deviation between Total Theoretical Energy measured by PV Pyranometer and Total Actual Energy Measured by the Wattmeter = 0.30%

Percentage deviation between Total Theoretical Energy measured by Thermopile Pyranometer and Total Actual Energy Measured by the Wattmeter =0.56%

5.6 Test day 6

The test results of Day 6 (26/11/2023) are given below

For Bifacial PV module

Time of the day	Irradiation in PV pyranometer (W/m^2/h)	Irradiation in PV pyranometer-Bifacial (W/m^2/h)	Theoretical Energy calculated using PV Pyranometer	Actual Energy measured in Wattmeter (Wh)
09:00 AM	261.10	24.32	217.88	244.30
10:00 AM	396.23	35.86	329.84	370.24
11:00 AM	686.92	43.71	557.73	564.39
12:00 PM	591.78	34.55	478.11	388.91
01:00 PM	516.37	32.03	418.63	398.39
02:00 PM	235.16	19.28	194.23	174.16

Table 5.11 Experimental data results of bifacial PV on test day 6

Total Theoretical Energy Measured by the PV Pyranometer in the day (6 hours) = 2,196.42 W/m^2

Total Actual Energy Measured by the Wattmeter in the day (6 hours) = 2140.39 Wh

Percentage deviation between Total Theoretical Energy measured by PV Pyranometer and Total Actual Energy Measured by the Wattmeter = 0.56%

For Halfcut PV module

Time of the day	Irradiation in PV pyranometer (W/m^2/h)	Irradiation in Thermopile Pyranometer (W/m^2/h)	Theoretical Energy calculated using PV Pyranometer	Theoretical Energy calculated using Thermopile Pyranometer	Actual Energy measured in Wattmeter (Wh)
09:00 AM	345.96	338.81	250.70	245.51	244.32
10:00 AM	519.72	575.46	376.61	417.00	371.47
11:00 AM	598.50	647.75	433.70	469.38	510.72
12:00 PM	697.63	649.38	505.53	470.57	523.11
01:00 PM	608.91	528.26	441.24	382.80	446.85
02:00 PM	379.13	299.64	274.73	217.13	256.19

Table 5.12 Experimental data results of halfcut PV on test day 6

Total Theoretical Energy Measured by the PV Pyranometer in the day (6 hours) = 2282.50 Wh

Total Theoretical Energy Measured by the Thermopile Pyranometer in the day (6 hours) = 2202.39 Wh

Total Actual Energy Measured by the Wattmeter in the day (6 hours) = 2352.66 Wh

Percentage deviation between Total Theoretical Energy measured by PV Pyranometer and Total Actual Energy Measured by the Wattmeter = 0.70%

Percentage deviation between Total Theoretical Energy measured by Thermopile Pyranometer and Total Actual Energy Measured by the Wattmeter =1.50%

5.7 Test day 7

The test results of Day 7 (07/12/2023) are given below

For Bifacial PV module

Time of the day	Irradiation in PV pyranometer (W/m^2/h)	Irradiation in PV pyranometer-Bifacial (W/m^2/h)	Theoretical Energy calculated using PV Pyranometer	Actual Energy measured in Wattmeter (Wh)
09:00 AM	337.15	33.65	283.05	328.96
10:00 AM	641.31	48.28	526.40	503.31
11:00 AM	811.14	60.49	665.37	661.43
12:00 PM	941.53	65.66	768.85	679.90
01:00 PM	788.84	43.53	635.40	576.68
02:00 PM	286.30	26.70	238.93	226.53

Table 5.13 Experimental data results of bifacial PV on test day 7

Total Theoretical Energy Measured by the PV Pyranometer in the day (6 hours) = 3118.00W/m^2

Total Actual Energy Measured by the Wattmeter in the day (6 hours) = 2976.81 Wh

Percentage deviation between Total Theoretical Energy measured by PV Pyranometer and Total Actual Energy Measured by the Wattmeter = 1.41%

For Halfcut PV module

Time of the day	Irradiation in PV pyranometer (W/m^2/h)	Irradiation in Thermopile Pyranometer (W/m^2/h)	Theoretical Energy calculated using PV Pyranometer	Theoretical Energy calculated using Thermopile Pyranometer	Actual Energy measured in Wattmeter (Wh)
09:00 AM	384.74	380.18	278.26	275.36	291.36
10:00 AM	637.29	596.54	461.59	431.88	454.51
11:00 AM	693.11	617.79	502.17	447.10	457.05
12:00 PM	803.85	784.20	581.88	568.12	523.64
01:00 PM	704.04	679.33	510.14	492.27	562.47
02:00 PM	437.25	405.62	316.67	293.48	328.30

Table 5.14 Experimental data results of halfcut PV on test day 7

Total Theoretical Energy Measured by the PV Pyranometer in the day (6 hours) = 2,652.38 Wh

Total Theoretical Energy Measured by the Thermopile Pyranometer in the day (6 hours) = 2,509.90 Wh

Total Actual Energy Measured by the Wattmeter in the day (6 hours) = 2617.33 Wh

Percentage deviation between Total Theoretical Energy measured by PV Pyranometer and Total Actual Energy Measured by the Wattmeter = -0.35%

Percentage deviation between Total Theoretical Energy measured by Thermopile Pyranometer and Total Actual Energy Measured by the Wattmeter =1.07%

6

Results

6.1 Comparison between Bifacial PV module and Halfcut PV module

In Bifacial PV module

Total Actual Energy Measured by the Wattmeter in 7 days = 18,369.38 Wh

Average Actual Energy Measured by the Wattmeter in 1 day = 2,624.19 Wh

In Halfcut PV module

Total Actual Energy Measured by the Wattmeter in 7 days = 16,969.53 Wh

Average Actual Energy Measured by the Wattmeter in 1 day = 2,424.22 Wh

Difference between Bifacial and Halfcut PV module

Total Actual Energy Measured by the Wattmeter in 7 days = 1,399.85 Wh

Average Actual Energy Measured by the Wattmeter in 1 day = 199.97 Wh

6.2 Comparison between PV pyranometer and Thermopile pyranometer

Total percentage deviation between Total Theoretical Energy measured by PV Pyranometer and Total Actual Energy Measured by the Wattmeter (7days) = 3.44%

Average percentage deviation between Total Theoretical Energy measured by PV Pyranometer and Total Actual Energy Measured by the Wattmeter (7days) = 0.57%

Total percentage deviation between Total Theoretical Energy measured by Thermopile Pyranometer and Total Actual Energy Measured by the Wattmeter (7days) = 7.29%

Average percentage deviation between Total Theoretical Energy measured by Thermopile Pyranometer and Total Actual Energy Measured by the Wattmeter (7days) = 1.21%

7
Conclusions

In this thesis, the Performance ratio of two types of Photovoltaic modules namely bifacial photovoltaic (PV) modules and half cut PV modules were studied numerically and experimentally, using two different types of pyranometers namely Photovoltaic pyranometer and Thermopile pyranometer.

Their performances were measured in two ways: the first was simply by noting the daily productions of each module technology, in the second case performance ratio measurement was done using two different types of pyranometer sensors namely Photovoltaic pyranometer and Thermopile pyranometer. These experimental activities were carried out under different time periods of the day in order to compare the effect of the Sun's irradiance level on the performance ratio. The data was recorded using a dedicated data acquisition system.

The principal observations are :-

- In the comparison between the energy production efficiencies of the two types of PV modules namely Bifacial PV module and Halfcut PV module, from this study it is observed that the Bifacial PV module is 7.92% more efficient in energy production.

- In the comparison between the accuracy between the two types of pyranometer sensors namely Photovoltaic pyranometer and Thermopile pyranometer, from this study it is observed that the Photovoltaic pyranometer is 3.85% more accurate in measuring the energy production.

Other future possibilities :-

- More different types of PV modules can be compared and studied.
- The experimental setup can be studied at different times of the year to understand the effect of seasons.
- The experimental setup can be studied at different geographical locations to understand the effect of location.
- Effect of different types of ground surfaces can be studied for Bifacial PV modules.

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