PREDICTION AND ANALYSIS OF OUTDOOR PERFORMANCE OF DIFFERENT SPV TECHNOLOGIES IN COMPOSITE CLIMATIC ZONE

A thesis submitted to the
University of Petroleum and Energy Studies

For the award of
Doctor of Philosophy
In
Engineering (Power)

By
Yogesh Kumar Singh

Feb 2023

Supervisor(s)
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Research and Development
School of Engineering
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Dehradun - 248007: Uttarakhand

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UPES
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Dedicated

To

My father,

Uma Shankar Singh

And

my mother,

Manju Singh

Feb 2023

DECLARATION

I declare that the thesis entitled "**PREDICTION AND ANALYSIS OF OUTDOOR PERFORMANCE OF DIFFERENT SPV TECHNOLOGIES IN COMPOSITE CLIMATIC ZONE**", has been prepared by me under the guidance of Prof. Santosh Dubey, University of Petroleum and Energy Studies, Dr. Kailash Pandey University of Petroleum and Energy Studies & Dr. O. S. Sastry, Maxop Research & Testing Institute Pvt. Ltd. No part of this thesis has formed the basis for the award of any degree or fellowship previously.

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CERTIFICATE

This is to certify that the thesis entitled "**PREDICTION AND ANALYSIS OF OUTDOOR PERFORMANCE OF DIFFERENT SPV TECHNOLOGIES IN COMPOSITE CLIMATIC ZONE**" is being submitted by YOGESH KUMAR SINGH (Sap Id 500044512) in fulfilment for the Award of DOCTOR OF PHILOSOPHY in the Department of Engineering Power of the University of Petroleum & Energy Studies. Thesis has been corrected as per the evaluation reports dated 12/12/2022 and all the necessary change / modifications have been inserted / incorporated in the thesis.

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ABSTRACT

The sustained growth of photovoltaic (PV) module installations in the energy market has led to the need of a reliable performance analysis of different PV technology modules. Performance of a PV module is affected by a number of environmental parameters such as ambient temperature, wind speed and direction, humidity, solar intensity and spectral distribution of irradiation, etc. The present work deals with understanding the effect of environmental parameters on the performance of different PV technologies such as multi-crystalline-Si (mc-Si), Cadmium Telluride (CdTe), Copper Indium Gallium diselenide (CIGS), amorphous-Si (a-Si), hetero-junction with an intrinsic thin-layer (HIT) and Integrated back contact technology (IBC). The performance analysis has been done in different Indian Climatic zones by considering a representative location from each zone: hot and humid (Chennai), hot and dry (Jodhpur), temperate (Bangalore), cold (Leh) and composite (Gurugram). Several tools like PVSOL, PVSYST, Artificial Neural Network (ANN), uncertainty analysis, have been used to carry out the performance analysis. The simulation software PVSOL has been employed for the performance assessment of all the technology modules mentioned above. The range of performance ratio (PR) of all the module technologies has been found to vary from 0.76 to 1.04. The performance assessment efficacy of PVSOL has been validated by comparing it with the performance estimated using the real-time data obtained from all the module technologies installed at the National Institute of Solar Energy (NISE) campus located in Gurugram (composite conditions). Trends of the performance ratios in each module technologies calculated using PVSOL and that using real-time field data have been found to be almost the same: the mean percentage change in PR values has been estimated approximately to be 2% in CdTe, CIGS, and a-Si modules technologies and 3% in mc-Si, HIT and IBC.

Knowing the performance of PV technology panels under prevailing conditions helps us in selecting a particular technology panel over the others for developing a power plant. The next issue is to predict the expected energy generation by the power plant, expressed in terms of P-50, P-90 and P-95 probability values, which give the probability of production level in a particular year. In order to perform this investigation, we have used a simulation software “PVSYST”, which calculates the P50, P90 and P95 probability values for various module technologies installed in composite climatic conditions prevailing in India. For a-Si technology, P50, P90 and P95 values are estimated to be 1528 kWh, 1458 kWh and 1439 kWh, respectively. The P50, P90 and P95 values for HIT technology are found as 2698 kWh, 2576 kWh and 2541 kWh, respectively. Similarly, for mc-Si technology the P50, P90 and P95 values are found to be 2378 kWh, 2614 kWh and 2579 kWh, respectively.

A comprehensive module characterization with the related uncertainty analysis has been carried out for CdTe and Micromorph PV technology modules by using the real electrical parameters measured at the

operating field conditions. The impact of cracks in the PV module on the I-V curve has also been evaluated. A power drop of 49% has been recorded in micromorph PV modules as a result of 24% reduction in the panel area due to crack defects. The performance assessment of both the technology PV modules has been initially carried out over a period of one year field exposure. Irradiance, temperature and spectral effects have been identified to quantify the corresponding losses/gain in power generation. The performance ratios of CdTe and micromorph PV modules have been found to be 80% and 65%, respectively. Spectral and thermal losses up to -29.2% and -10.1%, respectively have been recorded in the micromorph PV module. However, both the PV module technologies results are found to be insensitive to the irradiance effects with negligible losses, of approximately -1%. Overall, the CdTe module technology is found to be more efficient than the micromorph PV modules in composite climate of India.

In order to quantify the differential role of various weather parameters (like ambient temperature, wind speed, wind direction, humidity, irradiance, etc.) on the efficiency of a particular technology module, we employed ANN tool (nntool in Matlab) on the actual field data obtained from outdoor test-bed set ups and weather sensors installed at NISE campus, Gurugram. Since module temperature plays a deciding role in the efficiency, we used ANN tool to predict module temperature under the prevailing weather conditions. Then we compared the predicted module temperature with the actual module temperature data (as recorded by the sensors in the PV panels). The suitability of Artificial Neural network for these types of investigations is thus verified by the calculated overall coefficient of correlations (R= 99.16%) and regression coefficient (R^2 = 98.34%).

In summary, the work presented in this thesis presents a detailed investigation of some of the important aspects of PV module performance, which are relevant for different Indian environmental conditions using various techniques like PVSOL, PVSYST, ANN and uncertainty analysis.. The results and methodologies presented in this work will be helpful in investigating the variability in power generation due to environmental effects. Furthermore, this work might also help in the selection of an appropriate PV technology in a particular set of climatic conditions prevailing in India. In addition, the current investigation might help in listing out important installation recommendations for the installers, manufacturers and consumers under prevailing Indian climatic conditions.

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LIST OF SYMBOLS

I_{SC}	Short-circuit current
V_{OC}	Open-circuit voltage
I_L	Light generated current
I_D	Diode current
P_{max}	Maximum power
I_{max}	Maximum current
V_{max}	Maximum voltage
R_S	Series resistance
R_{sh}	Shunt resistance
I_{sh}	Shunt current
Y_f	Final yield
Y_r	Reference yield
P_o	DC output power
G_t	In-plane irradiance
λ	Wavelength
E	Spectral irradiance
q	Electronic charge
Φ	Spectral photon flux density
T_m	Module temperature
T_a	Ambient temperature

V_w	Wind speed
h_w	Heat convection coefficient
η_m	Module efficiency
η_{STC}	Module efficiency at STC
β_{STC}	Temperature coefficient of power at STC
$(\tau\alpha)$	Transmittance and absorptance product

LIST OF ABBREVIATIONS

AM	Air mass
AOI	Angle of incidence
APE	Average photon energy
ARC	Antireflective coating
a-Si	Amorphous- Silicon
BOS	Balance of system
CdS	Cadmium sulphide
CdTe	Cadmium telluride
CIGS	Copper indium gallium Selenide
EPC	Engineering Planning and Construction
EVA	Ethylene vinyl acetate
HIT	Hetero-junction with Intrinsic Thin layer
IEC	International Electro-Technical Commission's
ISA	International Solar Alliance
JNNSM	Jawaharlal Nehru National Solar Mission
LCOE	Levelized cost of energy
mc-Si	Multi crystalline Silicon
MFC	Most frequent condition
MMF	Mismatch factor

MNRE	Ministry of New and Renewable Energy
NISE	National Institute of Solar Energy
NOCT	Nominal operating cell temperature
NCPRE	National Centre for Photovoltaic Research & Education
PR	Performance ratio
PTC	PVUSA test condition
PV	Photovoltaic
PVF	Polyvinyl fluoride
PVUSA	Photovoltaic utility scale application
SHJ	Silicon hetero-junction
STC	Standard Test Condition
TCO	Transparent conducting oxide
TMY	Typical Meteorological Years
UF	Useful fraction

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CHAPTER 1
INTRODUCTION AND OBJECTIVES

1.1 Statement of the Proposal

1.1.1 Problem Statement

The aim of the current research work is to analyze and predict the outdoor performance of different SPV module (mC-Si, HIT, a-Si, CdTe, CIGS and micromorph) technologies in composite climatic zone of India. In addition to predicting the performance, this work also makes an effort to suggest different methods for increasing overall performance of different SPV module technologies.

1.1.2 Background

The growing energy needs throughout the globe and scarcity of the conventional energy resources such as coal, oil and gas has switched the interest of researchers towards renewable energy sources for energy production. This is evident by the fact that in last 15 years, the renewable energy industry has grown at a rapid rate. The energy generation using sun as the source has widespread advantages over conventional energy sources, which involves both environmental and economic factors. In the quest of clean energy production and avoiding over-dependence on fossil fuels for power production, India has set ambitious solar energy generation targets under the Jawaharlal Nehru National Solar Mission (JNNSM). In this mission, 100 GW (40% of which is to come from rooftop projects and rest from ground-mounted large scale solar power plants) of solar energy production target has been set. In order to achieve this target, the target module employed should have satisfactory long-term performance and reliability. The financial success of these projects depends on the total energy generation during the guaranteed lifetime of these systems (usually 25 years).

1.1.3 Motivation/Need for the research

India has destined to achieve 100 GW solar energy target by the year 2022. The realization of this goal necessitates improving the PV system's performance and reliability, load management & sharing, continuous power supply, and forecasting. Therefore, it is important to understand various factors and mechanisms which control the PV system's performance and reliability in outdoor conditions. The effect of weather conditions on the PV module's performance is considerable, which should be quantified either by experimentation or by simulations or both.

1.1.4 Objectives

The main objectives of the present study are:

1. To understand and analyze the effect of weather conditions on the performance of different PV technologies panels under composite climatic conditions.
2. To forecast /predict the performance of different technologies PV panels in composite climatic conditions using the predicted meteorological data.
3. To assess the relationship between various dependent and independent parameters and establish correlations between them.

1.2 Introduction

Renewable energy sources are emerging as the main established sources of energy worldwide. Renewable energy, often known as green energy. The energy derived from sources that are made available by nature and are not regenerated /exhausted over time. Wind energy, solar energy, geothermal energy, tidal energy, biofuel, and hydro energy are examples of renewable resources. 30% of the world's electricity is generated by renewable sources. By 2050, it is predicted that alternative or renewable energy sources would provide the majority of the world's energy needs. For more than seven years in a row, Costa Rica has produced a staggering 98% of its electricity from renewable sources using a combination of hydro, geothermal, wind, biomass, and solar power. In terms of installed renewable energy capacity, India is ranked fourth in the world, and over the last seven years, the country's non-fossil fuel energy production has increased by over 25%.

The most essential aspect of renewable energy is that it may be used without releasing damaging poisonous chemicals into the environment. Non-renewable energy sources, such as coal, oil, and gas, are expected to diminish in the future. Oil reserves will last 30 to 40 years at current consumption rates; gas reserves will last 50 to 60 years; coal stocks will last 80 to 100 years, and uranium reserves will last 1000 years. Renewable energy options are eco-friendly and help us lessen carbon foot print. In addition, renewable energy makes use of readily available energy sources all over the world, particularly in rural and distant locations that would otherwise lack access to electricity.

The last few decades have been an unexpected ones, for renewable energy, due to biggest annual growth ever. In order to deal with the global challenges of energy security, safety, reliability and sustainable development, there is a need to promote the innovative clean energy technologies. Among various renewable energy sources available nowadays, solar photovoltaic is playing a pivotal role in becoming the most sought after energy technology towards producing low carbon energy. It is, therefore, important to study these technologies in more detail, keeping in view the environmental impact on their performance, particularly in Indian environmental conditions. From a global viewpoint, such related environmental study on PV performance have been conducted on limited sites mainly in Europe, Japan and USA. This is one of such comprehensive studies performed on almost all existing PV module technologies under prevailing Indian environmental conditions. India has very different climatic conditions compared to other sites worldwide where similar studies have been performed, hence the results obtained in this work have potential in further improving our understanding of the performance of different PV module technologies in myriad environmental conditions, which would help us in future proofing our dependence on green energy harvesting via Solar PV.

Electrical power is vital for the economic growth of a country, and this is true for India also. In order to maintain the growth pace, uninterrupted availability of power supply is necessary. Although, Indian power sector is the fourth largest in world, still the per-capita electricity consumption is only about one-fourth of the world average. In a recent estimate, per capita energy consumption in India is around 1208 KWh (2019-2020) [1], which is the lowest across the globe. Low consumption of electricity is due to the lack of access of electricity to a larger proportion of the population. The demand of electricity by the year 2032 is estimated to be as high as 900 GW. As per the preliminary estimates of Demand projection, the all India peak electricity demand and electrical energy requirement is estimated to be 272 GW and 1,874 billion units (BU) for the year 2026-27 and 363 GW and 2,538 BU for the year 2031-32, respectively [2]. This clearly explains the need to increase the power production capacity at a rapid pace for the next several decades. Since the conventional sources (e.g. fossil fuels) are limited in extent, the focus of the policy makers is slowly shifting towards the renewable resources. The need to shift towards clean energy solutions is important also from the point of view of sustainability and environmental impact. Therefore, it is important to produce zero carbon emission electrical power, which can accelerate the growth rate of various industries. This led to the promotion of solar energy by Government of India by launching Jawaharlal Lal Nehru National Solar Mission on 11th January 2010. It is a joint effort of the Government of India and its state governments and is basically to promote ecologically sustainable growth keeping in view the challenges of energy security of the country and also to contribute towards the global effort to meet the challenges of climate change [3]. The solar energy target decided by Government of India is around 100 GW by the year 2022, which is several times bigger than the presently installed capacity of around 50.30 GW (dated 31-01-2022, CEA India). In comparison to solar power, thermal power producing systems (e.g. by using coal, gas and diesel) generate around 235.91 GW of power, nuclear power's share is around 6.78 GW, hydro power's contribution is around 46.51 GW and power from renewable energy resources is pegged at around 105.85 GW (see Table 1.1 & 1.2 for details) [4] . The harvesting of solar energy has been not been optimal so far, since the presence of solar radiation in India is around 850 W/m^2 for almost 300 to 320 days, and only a fraction of this has been harvested so far [5].

Table 1.1 All India Installed capacity (in GW) [4]

Sr. No	Mode wise backup	Installed capacity (GW)
1	Thermal	235.91
2	Nuclear	6.78
3	Hydro	46.51
4	Renewable energy	105.85
	Total	395.07

Table 1.2 Renewable energy Installed capacity (in GW)

Sr. No	Renewable energy sources	Installed capacity (GW)
1	Small Hydro Power	4.83
2	Wind Power	40.10
3	Bio-Power	10.17
4	Solar Power	50.30
5	Waste to Energy	0.43
	Total	105.84

1.2.1 Solar Energy Fundamentals

Solar energy may be utilized either in solar thermal or solar photovoltaic technologies. In solar thermal technologies, solar energy is harnessed to generate thermal energy, which is further converted to electrical energy for use in industrial/commercial areas, residential as well as in rural areas for several applications [6]. The applications of solar thermal energy are the following:

- Low temperature solar heating and cooling systems (e.g. solar driven cooling, solar heat driven ventilation, etc.),

- Medium temperatures heating via collectors (e.g. solar drying, cooking and distillation)

- High temperature heating via collectors (parabolic reflector, enclosed trough, power tower design heliostats', dish design, Fresnel reflectors, parabolic tough, heat collection and exchange, heat storage for space heating).

Solar photovoltaic system works on the principle of photovoltaic effect to convert light to electricity using photovoltaic/solar cells. The conventional solar cells used nowadays consist of p and n type semiconductor materials sandwiched together to make pn junction [7]. When light energy falls on a PV cell, mobile charge carriers, called as holes (+ve) and electrons (-ve), are generated by a process known as photoelectric effect. Under the influence of junction electric field, charge carriers are separated in such a way that holes are collected on the p side and electrons are collected on the n side of the cell. The charge segregation results in a potential difference across the cell, which is known as photovoltaic (PV) effect. PV effect is the fundamental mechanism responsible for power production from a solar cell [8].

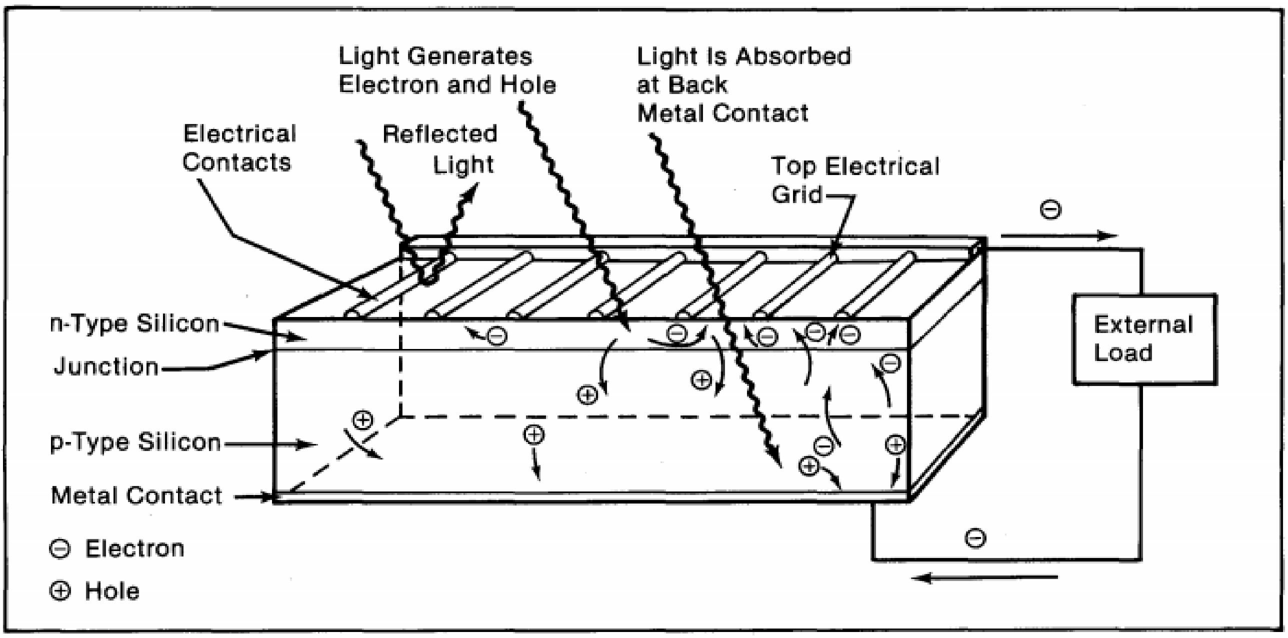


Figure 1.1 PN-junction diode as a solar cell. Generation of electron-hole pairs through light, and their separation by the potential barrier, creates a voltage that drives a current through an external circuit. [9]

The performance of the photovoltaic cell depends on many parameters such as the environmental factors and the material characteristics. These are given in detail as below.

1.2.2 Parameters affecting efficiency of a solar photovoltaic module and cell

Temperature – Thermal behavior is an important characteristic of a particular module technology. In standard test conditions (STC) conditions, the module behavior is usually optimal. In outdoor conditions, when the ambient temperature changes, the module performance changes accordingly. The greater the temperature, the maximum voltage loss is observed. Reduction in the voltage leads to reduction in the output power, which affects the overall efficiency of the module.

Irradiance- The amount of energy received per unit area per second is called irradiance. Irradiance affects module performance. If irradiance is low, the current output will be low, and vice versa. Irradiance behavior also depends on location, orientation and various other metrological data.

Spectral response- It refers to the ratio of current generated in solar cell to power incident on solar cell. It is analogous to quantum efficiency, which relates to the electron hole pair generated per incident photon in the solar cell.

Cloud movements - Sometimes cloud movements also play an important role in power generation. If there is a sudden cloud cover over the PV modules, the electricity generation from a solar panel drops drastically, leading to fluctuations in the output, which is undesirable. Therefore, reliable solar power production, prediction analysis should account for the correct cloud movements.

Humidity- Humidity plays a vital role in solar energy production. Results obtained so far indicate that the output current, voltage, and power increases (and hence efficiency) with low relative humidity.

Wind speed – Wind speed also affects the module performance. Generally, wind reduces thermal losses and increases power production by the modules. The wind load and wind velocity pressure depends on the shape of the module component..

Soiling behavior - Dust particles also play an adverse role in the efficiency of the power production. The dust particles on the surface of panels reduce the performance of the panels. Because of soiling, shadow regions are produced on the panels. The energy yield of a PV installation is reduced because of module soiling; this is prominent for framed modules and small tilt angles.

Incidence angle mismatch (IAM) losses –The output of a solar panel also depends on the angle of incidence of the sunrays and the intensity of the solar radiation. In order to calculate the least annual angle of incidence, the most optimum tilt angle of the panel is required. On March 21, the sun at solar noon makes a zenith angle (Φ) equal to the latitude of the place making the angle of incidence to be at the minimum. On June 21, the position of the sun at solar noon shifts by -23.45 degrees w.r.t zenith angle. On December 21, the position of the sun shifts by +23.45 degrees w.r.t zenith angle. Therefore, in a given year, sun shifts from Φ + 23.45 to Φ - 23.45 degrees. For a fixed panel, therefore, the optimum angle of tilt is the latitude of the location.

Module quality – Module quality is an important parameter to generate an optimum amount of power. Carefully installed with high quality components of a PV installation ensures trouble free operations for years with a reliable energy delivery. For instance, the module connection quality has improved significantly since the widespread use of plug connectors, which has helped to contain the losses.

Module Mismatch – Interconnections of PV modules not having identical properties or having different operating conditions results in mismatch losses. These types of losses are of serious concern in PV modules and arrays because under worst-case conditions, the solar cell with the lowest output gives an estimate of the total output of the entire PV module. A shaded portion in a PV module will hamper the overall performance as the unshaded portion generates optimal power but the shaded one does not, which results in overall less power generation and can lead to highly localized power dissipation and the resulting local heating may cause irreversible damage to the module.

Light-induced degradation (LID) - Physical reactions (electrons flow) through the p-n junctions of a PV module cause a natural degradation of silicon PV modules. However, the concept of (initial) "Power Stabilization" should be employed more generally. When modules are exposed to sunlight, they experience an initial decline called power stabilization. In manufacturer's datasheets, the typical percentage of power loss for the first year is usually indicated as being around 3%. For the following few years, "Power Degradation" is expected to be around 0.8% after the so-called "Power Stabilization."

Shading analysis- Shading analysis is very important to ensure maximum output. A thumb rule is that the distance between the obstacle and the solar panel should be at least twice the height of the obstacle. The cause of shading on a panel can be due to many factors, such as objects in the vicinity like trees, building, electric pole, presence of dirt, leaves etc. on the surface of the panel. Solar panel layout design has to be proper such that one panel does not cause a shade on another.

Potential-induced degradation (PID*)* – PID is most common when strings of modules operate at high voltages (1000 V to 15000 V) in extremely hot and humid conditions. The PID phenomenon may be catalysed by dust and glass deterioration (release of sodium ions). PID-affected modules (generally from the negative pole side of a string) typically show a pattern of "black" cells, or cells that were turned off closer to the module's frame. The flow of negative charges in the presence of extra positive charges could explain this pattern. An IEC standard (yet in draught form) is being developed to verify the resilience of PV modules to the PID phenomena. Basically, one of the approaches involves exposing PV modules to 1000 V (DC) for 96 hours inside a climate chamber with 85 % Rh and 60ºC

Module aging/degradation- In a PV system, modules are the most long-lasting components. Some crystalline modules have been in use for more than 25 years and exhibit no indications of wear and tear. The sun's UV light induces ageing and results in cell bleaching and mild deterioration over time. The term "degradation" refers to a reduction in a solar module's electrical output power over its lifetime. Weathering can cause damage to the plastic cell encapsulation, which can lead to corrosion in some situations.

Reliability- The quality and reliability of PV installations is a major concern that need to be understood to predict the performance of the plant. The contribution to the energy supply by a PV installation is worth only if it works properly

Durability- It is critical to build new device structures, develop encapsulation, and understand the degradation mechanism, and so on in order to increase device stability and longevity.

1.2.3 Types of PV systems and module technologies

Solar photovoltaic may be used in three ways:

- On-grid type application
- Off grid type application
- Hybrid type application

In **On-grid system**, there is no need for a battery backup. The inverter receives the power generated by the PV panels directly. **Off grid** system is also called the stand alone system. It is usually employed wherever the electricity supply from main utility grid is not possible or it is not cost effective. Standalone PV systems almost always necessitate the use of an energy storage system. , which consists of rechargeable batteries. Batteries running for long periods uses the charge controller, which works as a power management unit. In the off grid system, storage is important which is taken care by battery bank source.

Solar hybrid power systems: These systems combines the solar energy from a photovoltaic system to some other renewable or nonrenewable alternate energy source to generate electricity. A photovoltaic diesel hybrid system, which combines photovoltaic (PV) with diesel generators, or diesel gensets, is a common kind. PV with low marginal cost and is thus favored on the grid. The diesel generators used to bridge the gap between the current load and the PV system's actual generated electricity. Although solar energy fluctuates and the production capacity of diesel generator sets is limited, battery storage helps to maximize the solar PV contribution to the hybrid system's overall generation. More than one energy source is utilised in a hybrid system, which commonly consists of a combination of SPV-wind, SPV-hydro, SPV-biomass, SPV-DG set, or all of the combination may be used in the same way SPV-wind-hydro-biomass-DG set.

Module technologies: Depending on how the PV modules are built, it transforms only a portion of the light frequencies into power. Due to the cell material's limited ability to absorb light, solar PV modules dissipate the majority of incident solar energy. Numerous solar PV modules with various designs are being introduced in the market to make the most of the whole spectrum of light frequencies and boost module efficiency. Crystalline silicon (c-Si) solar cells, which may be mono – or multi-crystalline, make up the majority of solar PV modules currently being produced. These PV technology modules account for around 90% of the worldwide PV market. Due to a simple production technique, multi-crystalline silicon crystal can be produced at a lower cost than mono-crystalline. Multi-crystalline is made from inexpensive silicon, and it typically has slightly lower efficiency than mono-crystalline, ranging from 16 to 18 percent. This technology can help absorb more incoming light because it has a wide spectrum response and a band gap of about 1.1 eV. The temperature of the module may rise as a result of the light absorption. Due to its high temperature coefficient, the module's output power decreases as its temperature rises. Other technologies are amorphous silicon (a-Si), CdTe, CIGS, and micro morph, among the thin film category and high efficiency heterojunction intrinsic thin layer technology (HIT) and IBC belonging to high efficiency crystalline technologies. Because these technologies are so prominent in the PV industry, the PV modules in the same category have been evaluated and studied in this work.

The differences between crystalline and thin film solar modules are given in table 1.3. This table shows different types of technologies and their voltage ratings, temperature coefficients, fill factors and efficiencies.

Table 1.3 Differences between crystalline and thin film solar modules

Cell Technologies	Crystalline Silicon	Thin Film
Types of Technologies	Mono-crystalline silicon (c-Si)/ Poly-crystalline silicon (pc-Si/ mc-Si)/ String Ribbon/HIT/IBC	Amorphous silicon (a-Si)/Cadmium Telluride (CdTe) /Copper Indium Gallium Selenide (CIG/ CIGS)/Organic photovoltaic (OPV/ DSC/ DYSC)
Voltage Rating (V_{mp}/V_{OC}) (Higher is better as there is less gap in V_{OC} and V_{mp})	80%-85%	72%-78%

Temperature Coefficients	Higher	Lower (Lower is beneficial at high ambient temperatures)
Fill Factor	73%-82%	60%-68%
Module construction	With Anodized Aluminum	Frameless, sandwiched between glass; lower cost, lower weight
Module efficiency [10]	18%-22.5 %	12%- 19%
Required Area	Industry standard	May require up to %50 more space for a given project size
Example Brands	Kyocera, Evergreen, Sanyo, Schuco, Canadian Solar, Sharp,	First Solar, Solyndra, UniSolar, Konarka, Dye Solar, Bosch Solar,

1.2.4 Energy rating terms

Performance ratio – A location-independent metric known as the performance ratio is used to assess installation quality. The performance ratio (PR) is a manifestation of the total system efficiency and is defined as the ratio between a system's actual energy output and its nominal energy generation potential (system yield in ideal / STC conditions). According to IEC 61724 the PR is a measure of the system's real output in comparison to an ideal system that runs without losses.

$$\mathrm{PR} = \frac{\text{ENERGY YIELD}(Y_i\ )}{\text{RERERENCE YIELD}\ \ (Y_r)}$$

The performance ratio allows for a comparison of PV systems installed at various physical locations identified by differing weather conditions. The great majority of commercially accessible photovoltaic solar cells and modules employ silicon, in a variety of forms. Solar panels for both household and large-scale commercial photovoltaic systems are often made from single-crystalline, polycrystalline, or amorphous silicon. Depending on the applications, location, available area, aesthetics, and other factors, each of these technologies has a well-established price-to-performance ratio and specific cost and benefit benefits. Another form of PR definition

$$\mathrm{PR} = \frac{\text{Energy generated (kWh)}}{\text{Irradiance (kWh/m}^2\text{) on pannel} \times \text{ Area of PV module (m}^2\text{)} \times \text{PV module efficiency}}$$

Capacity Utilization Factor (CUF)

$$\mathrm{CUF} = \frac{\text{Energy generated (kWh)}}{\text{Installed capacity} \times 365 \times 24}$$

On the one hand, PR is a measure of a PV system's performance that takes into account environmental conditions (temperature, irradiance, etc.), CUF on the other hand ignores all of these elements as well as panel degradation.

Following list is prepared to compare PR and CUF: – The availability of the grid is taken into account by PR, but not by CUF.

– CUF does not take into account the minimal amount of irradiation required to generate electrical energy, but PR does.

– CUF does not take into account irradiation levels over time, whereas PR does. PR may be used to evaluate different solar PV systems

– Even if they are in different locations – because all environmental parameters are taken into consideration.

As a result, just the architecture and the system's ability to transform solar energy into electrical energy will be compared.

1.2.5 Economics of Solar Energy Production and Consumption

Simple payback is the time it takes to recoup the initial expenditure.

Return on Equity (ROE) - The total plant cost that is allowed in the base rate determines the equity. The amount of equity is influenced by the company's leverage. When calculating the cost of electricity and consequently the rate to be charged to the consumer, the ROE is applied to the equity and added to the cost.

Capital Charge Rate- This is the rate that will be applied to the plant's capital costs in order to transform capital costs (i.e. investment) into operating costs (or annual costs). This rate usually contains the majority of our apprehensions about the future (i.e. interest rates, ROE, inflation, taxes, etc.)

Discounted Cash Flow Analysis- Economists and developers prefer discounted cash flow analysis, which uses a spreadsheet to forecast cash flows across the project's life cycle.

Levelised cost of electricity (LCOE) - The cost per kWh of energy generated that takes into account the time worth of money is known as the levelised cost of electricity (LCOE). The goal is to keep the LCOE as low as possible. The cost and availability of land and plant components should also be addressed when deciding between high-efficiency/high-cost modules and low-efficiency/low-cost modules. Land, cabling, and support are all greatly reduced with high-

1.2.6 Organization of the thesis

The thesis is divided into 5 chapters. The first chapter provides a detailed introduction of the subject. Chapters 2 and 3 include discussion on research methodology, experimental setups, theoretical tools, test bed configuration, weather station and PV instrumentation, literature review on the effects of weather conditions, predictions and forecasting analysis, and degradation and durability of modules. Results and Discussion are included in chapter 4 followed by conclusion in Chapter 5.

CHAPTER 2

LITERATURE REVIEW

2.0 Introduction

In India, there are mainly five climatic zones: hot and humid, hot and dry, cold, composite and temperate **[14].** The suitability of a particular technology has to be decided vis-à-vis various climatic zones. There has been significant research in the past to understand the effect of different weather parameters such as the wind speed, temperature variance, irradiance, humidity, solar spectrum etc. on the performance of different PV modules. Keeping in view the importance of the topic, the literature review has been focused on weather conditions having an impact on PV panels, forecasting the performance of various technologies PV panels and analysis of the performance of the panels under varying weather conditions.

2.1. Effect of weather conditions

Christian Karcher et al [15] applied an electroluminescence set-up to investigate the voltage losses on PV panels induced by temperature change and explained it with a bandgap dependent rise in intrinsic carrier concentration. **N. Bogdanski et al [16]** investigated the electrical performance, mechanical condition, and visible alterations of different crystalline PV modules. These were fabricated by various German manufacturers and exposed to outdoor conditions in different climates such as warm moderate, tropical, cold and arid conditions. **Caluianu, Ionut-Razvan et al. [17]** developed a thermal model of a PV module and study the temperature and velocity profiles of the air at the exit section between the panel and the wall. They also studied the influence of the mounting distance on the temperature and velocity values. **R. Chenni et al. [18]** modelled three common types of solar panels made of different materials: CIS thin film, multi-crystalline silicon, and mono-crystalline silicon. They were able to illustrate the output properties of the cell in terms of irradiance and temperature changes in the surroundings. To demonstrate the efficacy of the proposed approach, a comparison evaluation of simulation results based on product manufacturer data was provided. Outdoor observations in Greece were used by **John K. Kaldellis et al [19]** to investigate the temperature and wind speed effect on the efficiency of PV installations under conventional test settings (STC). Based on in-situ measurements under changing weather circumstances, the study explored the influence of temperature change on the operation of commercial PV applications**. Balaska et al. [20]** investigated the outdoor I-V characteristics of CIS, HIT and tandem structure of amorphous silicon and microcrystalline silicon (a-Si c-Si)) and two crystalline silicon modules (multi-crystalline and mono-crystalline) in relation to various meteorological parameters such as irradiance, temperature, and humidity. They found that HIT, a-Si, and micromorph-Si modules performed better than modules from other technologies. **Sanaz Ghazi et al [21]** used measurements made in a clean laboratory setting at a temperature of 25^{o} C and a standard air density to investigate the effect of weather variables on the efficiency of PV panels. The influence of dust density on panel light transmittance was also investigated. The efficiencies of the two PV installations were shown to be significantly affected by a wide range of meteorological conditions like high humidity, rain, and snow. **R. Gottschalg et al. [22]** investigated the daily and seasonal fluctuations in the incident sun spectrum on solar cells. The "usable proportion" of light in amorphous silicon was found to be the most responsive to changes in the spectral distribution, ranging from +6% to 9% of the yearly average, with the largest occurring in the summer. After a few years of operation in a tropical environment, **Ababacar Ndiaye et al [23]** evaluated the degradation of monocrystalline-silicon photovoltaic modules and discovered that $P_{\max}, I_{\max}, I_{\mathrm{SC}},$ FF are the most damaged performance metrics for all the tested PV modules. **Premalatha L et al [24]** investigated the impact of dynamic weather conditions on three types of PV cell technologies (monocrystalline, multi-crystalline, and thin film), and presented an analysis of the impact of dynamic irradiance and temperature fluctuations on the performance of various PV cell technologies. All three PV technologies were shown to react differently to varying irradiance and temperature conditions, which altered their energy output**. Makbul A.M. et al [25]** researched the solar output power loss owing to dust deposition and weather conditions (e.g. humidity, cloud movement, rain, etc.). In an average relative humidity of 52.24%, two weeks of dust deposition resulted in a 10.8% reduction in PV power output. The results of the experiment demonstrated a decrease in PV output power of more than 40% in wet conditions with an average relative humidity of 76.32%, and a decrease in output power of more than 45% in cloudy conditions with an average relative humidity of 60.45% . **M.Shravanth et al [26]** investigated the efficacy of solar photovoltaic installations in Bangalore over various seasons and climate conditions. The SPV system's performance was assessed utilizing grading systems such as the Capacity Utilization Factor (CUF) and the Performance Ratio (PR). It was concluded that the PR of SPV systems is related to the behaviour of SPV modules in various seasons, with module temperature (T_{mod}) being a major comparative element. In a desert environment, **Ahmed Bouraiou et al [27]** investigated the effect of environmental factors on the performance of solar modules. After long-term exposition, numerous parameters of modules were damaged, including maximum output current (I_{max}), maximum output voltage (V_{max}), maximum power output (P_{max}), open-circuit voltage (V_{OC}), short-circuit current (I_{SC}), and fill factor (FF). **R. Eke et al. [28]** investigated the impact of spectrum irradiance on solar module outdoor performance. Some modules performed better than others at the same operating temperature for the same irradiance level. **Ahmad Vasel et al [29]** investigated the effect of wind direction on the performance of solar PV facilities in the United Kingdom. The wind direction and wind speed frequency were discovered to be important factors in site selection for solar PV plant installation. The study also found that solar PV plants with a fixed tilt that are aligned west east have the maximum efficiency. **Julius Tanesab et al [30]** investigated the seasonal influence of dust on the degradation of PV module performance in several climatic regions such as Perth, Western Australia, Indonesia, and others, and discovered that PV performance varied with season in both study locations. **C. Schwingshackl et al. [31]** studied the cooling effect of wind on Photo Voltaic cell temperature and discovered that among many models for predicting PV cell temperature, the one that includes wind data performs better. The researchers demonstrated that wind data from numerical weather prediction models can be used to substitute in-situ wind measurements. **Rachid Dabou et al. [32]** investigated the performance of grid-connected photovoltaic systems in south Algeria under various climatic conditions, which included high ambient temperatures, high solar insolation potential, and low humidity rates throughout the summer months. The lowest values of system efficiency and performance ratio (10.29% and 76.5%, respectively) were observed at a high module temperature of 41.1 °C on a clear day, according to the testing data. The researchers also discovered that changes in cloud cover and dust storms cause a shift in irradiance, which could affect stability and the amount of energy generated by the PV system**.** In hot and humid settings**, Nochang Park et al [33]** investigated the influence of moisture condensation on the long-term dependability of crystalline silicon solar modules. Based on environmental data monitoring, **Michael Koehl et al [34]** suggested an MC(moisture condensation)-induced deterioration prediction model for accelerated lifetime testing of humidity impact on PV-modules. **Rafael Moreno-Sáez et al [35]** used contour graphs for different outdoor situations to analyse and characterise solar modules from three different thin-film technologies. The module temperature, the atmospheric clearness index, and the solar spectral irradiance distribution were the most explanatory parameters they discovered. . **Vikrant Sharma et al. [36]** investigated the suitability of various solar photovoltaic technologies (polycrystalline silicon, HIT, and a-Si) in different Indian climates. In comparison to p-Si modules, the energy yield of a-Si modules was found to be 14% higher in the summer and 6% lower in the winter. HIT modules were found to regularly yield 4–12% more energy than p-Si modules. **Naoyasu Katsumata et al [37]** used meteorological data to evaluate the irradiance and outdoor performance of solar modules. The effects of irradiance, solar spectral distribution, and module temperature on photovoltaic (PV) module performance were observed to be significant**.** Under a hot and hard climate, **Alain K.Tossa et al [38]** investigated the energy performance of monocrystalline, two polycrystalline, and one tandem structure (amorphous/microcrystalline) also known as micromorph modules.

2.2 Prediction/Forecasting and analysis of PV panel's performance

Forecasting is an important part of ensuring optimal solar PV plant planning and modelling. Time-series statistical approaches, physical methods, and ensemble methods are the three basic categories of solar photovoltaic power forecasting methods. Artificial intelligence approaches, in addition to these methodologies, are frequently used due to their capacity to solve non-linear and complex data structures. **Marcantonio Catelani et al. [39]** proposed the failure modes, effects, and criticality analysis (FMECA) approach for classifying the occurrence, severity, and impact of all probable PV module failure mechanisms. Machine learning was used by **Amandeep Sharma et al [40]** to forecast daily global solar irradiance generation. FoBa-(Adaptive forward – backward greedy algorithm), leap Forward, spikeslab, Cubist, and bag Earth GCV models were used to make forecasts**. L. Mazorra Aguiar et al [41]** improved intra-day solar forecasting by combining solar irradiance measurements, satellite-derived data, and a numerical weather prediction model. **Imen Gherboudj et al [42]** used remote sensing and weather forecast data to analyse the solar energy potential across the United Arab Emirates. PVMAPS software tools and data were examined by **Thomas Huld et al [43]** for the estimation of solar radiation and photovoltaic module performance over vast geographical areas. **Priyanka Chaudhary et al [44]** created a hybrid model for solar energy forecasting that used neural networks and wavelet transform. The suggested model's performance was assessed using both root mean square error (RMSE) and mean absolute error (MAE). The results were compared to other current technologies such as ANN for validation and found to be better within specified limitations**. M. Malvoni et al. [45]** combined the Perez and Hay-Davies models for computing irradiance on tilted surfaces with three meteorological datasets, each with a different monitoring period and meteostation location, to estimate the POA irradiance, module temperature, and PV energy output for a PV system in the Mediterranean climate area. The PVsyst tool was used to make predictions, which were then compared to the actual data. Influence of wind on PV module performance was also taken into account during simulations. The results show that the geographic characteristics of the location where the weather station is located have a greater impact on PV system performance projections than the distance between the PV system and the weather station. **Jose-Mari, Delgado-Sanchez, and colleagues [46]** reviewed the main dangers to the CIGS thin-film technologies' commercial feasibility. The Failure Mode Analysis and Effects (FMEA) approach was used to determine the major reasons of the technologies' possible failures. To validate the results of the FMEA, ageing tests and outdoor monitoring were performed. Based on the findings, it was determined that the encapsulating material is the primary cause of CIGS module degradation**. Tao Ma et al. [47]** introduced a simulation model for modelling and performance prediction of photovoltaic (PV) systems. The well-known five-parameter model was chosen, and the problem was solved using a novel combination technique that combined an algebraic simultaneous calculation of the parameters under standard test conditions (STC) with an analytical determination of the parameters under real-world operating conditions. Under partially shadowed situations, **H. Mekki et al [48]** suggested a fault detection system for photovoltaic modules. Under fluctuating operating conditions, it used an artificial neural network approach to predict the output photovoltaic current and voltage. The data collected from Jijel University's Renewable Energy Laboratory REL (Algeria) (solar irradiance, cell temperature, photovoltaic current, and voltage) was used. To demonstrate the efficiency of the suggested technique, several shading patterns were studied. The findings revealed that the proposed method correctly detects the shadowing effect on the photovoltaic module. **Soteris A. Kalogirou et al. [49]** described several neural network applications in energy problems, including the modelling and design of a solar steam generating plant, the estimation of a parabolic-trough collector's intercept factor, and the modelling and performance prediction of solar water heating systems. A numerous hidden-layer architecture has been adopted in all of these experiments**.** **Ismail Kayri et al [50]** used an artificial neural network to predict the power generated by a monocrystalline silicon photovoltaic panel based on I-V data recorded from the panel for a year as a function of various environmental variables such as solar irradiance, air temperature, wind speed, wind direction, relative humidity, and angle of the sun's elevation. . **David Daz–Vico et al. [51]** used Deep Neural Networks (DNNs) in the forecast of wind energy and daily sun radiation, with inputs derived from Numerical Weather Prediction systems that have a distinct spatial structure. Single deep models, and especially DNN ensembles, can outperform Support Vector Regression, a Machine Learning technique that is regarded the state of the art for regression**.** Artificial Neural Network algorithms estimate solar radiation more correctly than conventional methods, according to **Amit Kumar Yadav et al [52].** The accuracy of ANN models' predictions was found to be influenced by input parameter combinations, training algorithms, and architecture configurations**.** Artificial neural networks (ANNs) were utilised by **S.A. Kalogirou et al [53]** to forecast the performance of big solar PV systems. **Youssef Mallal et al [54]** examine a temperature prediction-based approach for realistic performance analysis of various electrical PV panel setups. The suggested method was used with different solar photovoltaic systems (Series, Series-Parallel, Honey-Comb, Bridge-Linked, and Total-Cross-Tied). **B.Meng et al [55]** studies the performance differences between similar rooftop PV systems in the real world and develop risk-reduction measures to lessen the uncertainty in predicting annual yield. To accomplish the goal, 246 similar rooftop PV systems in 19 sub-urban residential communities' long-term monitoring data is evaluated. The mechanism of PV performance differences linked to location, module orientation, season, sky clarity, and system age is examined through systematic side-by-side comparisons. When compared to the nameplate bandwidth stated by the manufacturers, it is seen that PV performance variability increases in the actual built environment.

2.3 Durability and Degradation of solar modules

The degradation rates of PV modules measured annually are crucial in predicting yield. These rates are lower than the measurement uncertainty of a nominal power measurement made at today's most advanced certified photovoltaic reference laboratory for a high-quality PV module. As a result, the study necessitates a well-thought-out approach that may compare the data on an annual basis to each other or to an unused module stored in the dark **[56].** The performance degradation over a long time of different types of commercial crystalline silicon solar modules in tropical rainforest climates suggests that short circuit current loss I_{SC} is the main cause of degradation **[57]**. Linear Regression (LR), Classical Seasonal Decomposition (CSD), Auto Regressive Integrated Moving Average (ARIMA), and Locally Weighted Scatter plot Smoothing are the four basic statistical analysis approaches proposed for calculating degradation rates (LOESS) **[58]. Praveen et al. [59]** provided a model to assess the degradation of PV panels with various topologies using a clustering-based technique. The performance ratio (PR) of the PV panels is evaluated here without the need for on-site physical inspection, making the suggested model useful for real-time estimation of the PR and, as a result, for more reliable PV power production predictions. **Ismail et al. [60]** examined the power degradation, failure time, and remaining useful lifetime (RUL) of solar modules exposed in the field for 5 to 35 years, and created power degradation, failure time, and RUL models calibrated and validated using diverse module technology data. **Arechkik Ameur et al [61]** performed economic analysis along with long-term performance and degradation analysis of three silicon-based PV technologies—amorphous silicon (a-Si), polycrystalline silicon (p-Si), and monocrystalline silicon (m-Si) . The performance metrics used in this study are the amount of AC energy produced (EAC), the reference yield (Y_r), the final yield (Y_f), the performance ratio (PR), the temperature corrected performance ratio (PR_{STC}), the degradation rate (D_r), and the levelized cost of energy (LCOE). **Jaeun Kim et al [62]** studied various aspects of photovoltaic (PV) modules, regarded as the most dependable part of the PV systems study, the authors described various accelerated stress types and PV-module degradation types that are used to assess the reliability and durability of PV-modules for life expectancy before utilizing them in the actual applications. It was observed that outdoor-performance data should be utilized (instead of data under lab conditions) to assess a PV module's long-term performance under a variety of terrestrial circumstances. However, this necessitates a 25-year wait before the module reliability can be determined, which is exceedingly unfavorable. Therefore, accelerated stress testing carried out in the lab and simulations of various field situations prove to be crucial for figuring out how well a PV module performs. Under average operating conditions, there is a good chance that the PV module will continue to function properly for 30 years.

2.4 Research Gap

Despite the incredible successes of PV degradation and reliability analysis studies, particularly in terms of data-driven analytic modelling methodologies, there are still a number of unresolved issues which need to be taken care of for making solar energy harvesting and production of green electrical power sustainable . The qualitative and quantitative properties of the datasets and dataset production methods have a significant impact on the prediction models. The acquisition of sufficient and adequate datasets has remained a problem, as evidenced by the fact that the majority of recent research works used small amounts of data, while others used open-source datasets, data augmentation, and simulated datasets to obtain adequate datasets for classifications. Researchers' and academics' use of simulated datasets often reveals inconsistent prediction and classification. Additionally, using open-source datasets (some of which were obtained from fielded modules in a different climate) won't give a contextual assessment of the performance of the particular PV modules because the performance of field deployed PV modules depends greatly on the geographic climate at which they are being used.

The purpose of this thesis is to determine, for the Indian climatic conditions, the rates at which various types of PV Modules degrade through extensive outdoor testing. PV modules are susceptible to weather and natural conditions such as rain, snow, wind, soiling, etc. They degrade due to solar radiation, and, of course, meteorological conditions in addition to other factors. The determination of degradation rates would prove to be very important for the development of module technologies. The most crucial factor in mass production is cost-effective fabrication. For the investigation of advantages and disadvantages, information on the short- and long-term degradation and performances of these modules and cells is required. According to this viewpoint, it becomes increasingly important for businesses and researchers to evaluate solar modules in varied climates. In this thesis, 6 different solar modules' efficiencies, performance rates, corrected performance rates, and degradation rates are calculated, and the results are examined using long term database. In table 2.1 gives the research gap analysis.

Table 2.1 Research Gap Analysis

Sr No	Author(s)	Year	Source	Title	Research Gaps
1	Christian Karcher	2014	Progress in photovoltaics	Temperature-dependent electroluminescence and voltages of multi-junction solar cells	The degradation and performance parameters were not given because the focus was solely on EL image theory.
2	Ionut - Razvan Caluianu	2012	Applied Thermal Engineering	Thermal modelling of a photovoltaic module under variable free convection conditions	Using experimental data, a thermal model for a solar module was constructed and validated. The goal of this research was to only determine the temperature parameters.
3	R. Chenni	2007	Energy	A detailed modeling method for photovoltaic cells	It is described a general approach to modelling solar modules. The following points were selected for parameter determination under reference conditions: short-circuit current, open-circuit voltage, temperature coefficient of open-circuit voltage, temperature coefficient of short-circuit current,

					and maximum power point.
4	John K. Kaldellis	2014	Renewable Energy	Temperature and wind speed impact on the efficiency of PV installations. Experience obtained from outdoor measurements in Greece	The impact of weather conditions on existing only (m-Si) PV performance characteristics has been investigated.
5	Sanaz Ghazi	2014	Renewable Energy	The effect of weather conditions on the efficiency of PV panels in the southeast of UK	The impact of dust and bird droppings on panels
6	R. Gottschalg	2003	Solar Energy Materials & Solar Cells	Experimental study of variations of the solar spectrum of relevance to thin film solar cells	Only look at the performance of thin-film solar cells in a maritime environment.
7	Ababacar Ndiaye	2014	Solar Energy	Degradation evaluation of crystalline-silicon photovoltaic modules after a few operation years in a tropical environment	The impact of tropical climatic conditions on the performance deterioration of monocrystalline-silicon (mc-Si) PV modules and polycrystalline-silicon

					(pc-Si) Photovoltaic modules is investigated.
8	Nochang Park Changwoon Han	2013	Microelectronics Reliability	Effect of moisture condensation on long-term reliability of crystalline silicon photovoltaic modules	Moisture condensation (MC) in hot and humid areas, as well as water droplets on solar modules, are being investigated for corrosion analysis.
9	Michael Koehl	2012	Solar Energy Materials and Solar Cells	Modelling of conditions for accelerated lifetime testing of Humidity impact on PV-modules based on monitoring of climatic data	Water is regarded as a significant deterioration concern for PV modules since it causes hydrolysis of polymeric components, corrosion of glass, and corrosion of metallic components such as grids and interconnectors.
10	Vikrant Sharma	2013	Energy	Performance assessment of different solar photovoltaic technologies under similar outdoor conditions	Only three solar technology modules were studied for performance: polycrystalline silicon, hetero-junction with intrinsic thin-layer silicon, and amorphous single junction silicon.

11	Naoyasu Katsumata	2011	Solar Energy Materials and Solar Cells	Estimation of irradiance and outdoor performance of photovoltaic modules by meteorological data	Discuss how three environmental parameters, irradiance, solar spectral distribution, and module temperature, all have a significant impact on the performance of photovoltaic (PV) modules.

CHAPTER 3

RESEARCH METHODOLOGY

3.0 Introduction

The outdoor performance of different PV modules depends on various factors, which may be internal such as the material used for the construction of the module, etc. or external, which includes environmental factors such as temperature, wind speed, moisture and other climatic conditions. The external factors vary with the geographical locations where the modules are installed. Study of the outdoor performance thus will depend on the location of the SPV plant.

The performance analysis of the modules is viable for proper functioning of a SPV plant. There are different approaches to predict and analyze the outdoor performance of a SPV plant. Theoretical modelling based on the experimental results is one of the reliable approaches for such studies. In the present work, the theoretical tools such as the PVSYST, PVSOL, and ANN are used for prediction and analysis of the outdoor performance of SPV plant with different PV module technologies. The results obtained from the simulation tools were validated against the real time data from PV technologies physically installed at NISE campus, India (composite climate)

3.1 Proposed methodology

The following methodology is followed for the conduction of the current research investigation:

- Outdoor SPV test bed setup for all the technologies panels.
- Collection of predicted meteorological data from various sources like IMD, NIWE (CWET), etc.
- Generation of base data with different module technologies.
- Performance behavior data of different module technologies.
- Develop energy yield mapping in composite climatic zone.
- Generate performance and reliability data under different operating conditions.

- Development of energy forecasting in different module technologies in various climatic zone condition.
- Analysis and inference of the test data.
- Documentation, publications and thesis writing.

Weather conditions have an impact on the performance of several technologies. PV panels will be investigated utilizing methods such as least square regression, artificial neural networks, and simulation software like PVSYST and PVSOL.

3.2. Experimental Setup

PV test beds are the most convenient way to validate a PV technology for a particular site or for locations having different weather parameters. Researchers have designed and selected different capacity of PV arrays, data loggers, scanners for their test beds. In addition to developing test beds, it is also necessary to have an efficient data strategy, structure and format, which can be shared and a network may be established to help the researchers in the mapping of performance indicators over an area. The data of PV test beds as well as weather stations have been logged in a systematic format, which is used in the thesis work for estimation of environmental effects and thus analyze the performance of different PV technologies modules.

Following equipment/setup are available at National Institute of Solar Energy NISE outdoor tested facility, which were used for the proposed study.

- Multi-channel IV curve tracer
- 500 kWp solar power plant

NISE has installed a 500kWp multi-technology solar photovoltaic power plant to accomplish the day-to-day increasing energy requirement in campus, and provide the R & D infrastructure to study SPV module reliability of different technologies module with on-grid and off-grid configuration in composite climatic condition and study the smart grid design. The main idea is to provide uninterrupted power supply in the campus 24 x 7. The power plant consist of five different technologies split into two configurations: 200 kWp is connected to the battery bank and 300 kWp is connected to the grid. The detailed breakup of technologies and configuration is listed below.

Five Different Technologies and configurations of Plant

I. 100 kWp Battery Back-up SPP with Multi-crystalline modules
II. 100 kWp Battery Back-up SPP with Panasonic HIT© modules
III. 100 kWp Grid Tied SPP with CdTe modules
IV. 100 kWp Grid Tied SPP with CIGS modules
V. 100 kWp Grid Tied SPP Maxeon© Sun Power with single axis Tracking

3.3. Description of different technology PV modules

a) Multi-crystalline modules (Off Grid)

100 kWp (78 kWp +22 KWp) multi-crystalline technologies based power plant is connected to 2000 Ah battery bank. There are 400 Nos of modules; each module has a power rating of 250 Wp. The modules are mounted at 20° fixed tilt to obtain the maximum radiation throughout the year. In order to get the desired power, 26 strings have been made; in each string, there are 12 modules in series, which is connected further to two-string combiner box. The output of the strings is connected to 100 kVA Battery Inverter.

Figure 3.1 Multi crystalline Module

b) Panasonic HIT (Heterojunction with Intrinsic Thin-Layer) modules (Off Grid): HIT solar cell is a hybrid solar cell, composed of a single-crystal silicon wafer surrounded by layers of thin amorphous silicon. Panasonic HIT modules have a power rating of 100 kWp. In this project, 420 modules have been used at a fixed inclination of 20°. There are 60 strings of modules, and each string contains 17 modules. HIT based

Figure 3.2 HIT Module technology

power plant is also connected to a battery bank of 2000 Ah. Two combiner boxes are used to club the power output.

Figure 3.3 Plant Location

c) CdTe modules (On Grid)

First solar series 4 PV modules are used for CdTe test bed. The total number of modules installed in this test bed is 1000; each has a power rating of 100 Wp. Two combiner boxes have been used in this power plant. In combiner box 1, 14 modules are in series and 11 modules in parallel, and in combiner box 2, 14 modules in series and 11 modules in parallel.

Figure 3.4 CdTe module

d) CIGS modules (On Grid)

The Stion Corporation from USA supplies the CIGS modules, which has a power rating of 100 kWp and module peak wattage of 140 Wp (approx.). The modules are PID resistant, and have low LID effects. In combiner box 1, 10 modules are connected in series and 36 are connected in parallel. Combiner box 2 has 10 modules in series and 36 modules in parallel. All these modules are installed at fixed structure with 20° tilt.

Figure 3.5 CIGS module technology

e) Sun Power High Efficiency modules (On Grid)

The highest efficient commercially available panels in the market today, are the Sun Power E20 panels. The E20's have low temperature coefficient of voltage, are aided with anti-reflective glass, and have exceptionally low-light performance that attributes to outstanding energy delivery per watt peak. There are 308 modules, each having a power rating of 327 Wp, which are mounted on single axis tracking system equipped with advance weather monitoring system to sense the wind blowing speed and reorient the plant to a safer position during the wind speed of more than 160 kmph. This is achieved with the help of a sensor fitted at the center of the plant, which is connected through radio frequency signal to the wind fan and its control system. The power plant is connected through two-combiner box. Combiner box 1 & 2 has 14 modules in series and 11 modules in parallel.

Figure 3.6 Sun Power Module Technology

3.4 Smart Grid configuration

The smart grid schematic diagram is shown below. There are five different technologies and each technology is connected with a single 100 KVA inverter. A dedicated load connected to the battery bank system has been created in such a way that during the unavailability of the grid, battery connected power plant will work as the reference grid. The load management is done with SCADA software.

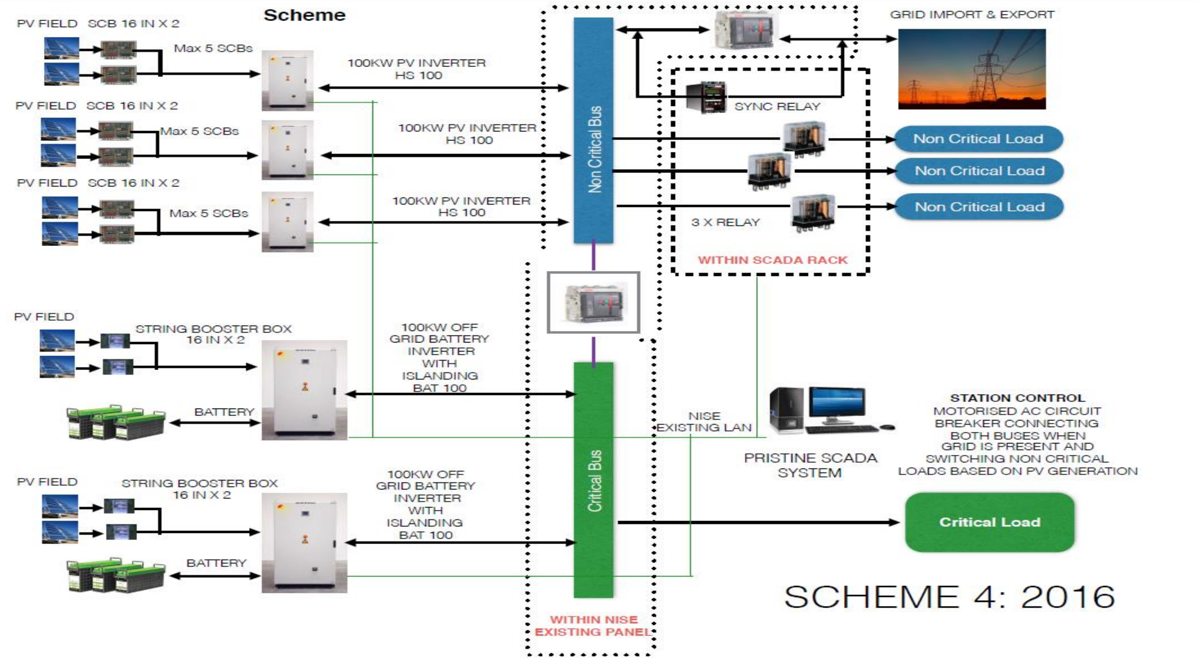


Figure 3.7 Smart Grid Schematic diagram

3.5 Test Bed Configuration

Six types of module technologies are used in this study as shown in Figure 3.8. These are multi-crystalline silicon, amorphous-Si thin-film module, HIT module, CdTe thin-film module, CIGS thin-film module, and IBC module. All the modules were installed at NISE campus having composite climatic conditions. In table 3.1, the number of modules used in series and parallel combinations are given. For 3.2 kWp solar plant using CdTe technology, forty modules are used for the analysis: ten modules in series and four modules in parallel. For CIGS modules, total plant capacity is 1.2kWp with a total of ten modules: ten modules in series and one module in parallel. The HIT plant capacity is 1.68Kwp, in which four modules are in series and two modules are in parallel. The a-Si plant capacity is 1.2kWp, in which four modules are in series and four modules are in parallel combination. mc-Si technology plant has the capacity of 1.58kWp, in which nine modules are in series and one module in parallel combination. The IBC plant capacity is 1.68kWp, in which five modules are connected in series and one module in parallel combination. Table 3.2 represent specifications of individual modules used in the test bed under STC. In Table 3.3 Physical dimensions and weight of six different module technologies and Table 3-4 PV module parameters of six technologies modules.

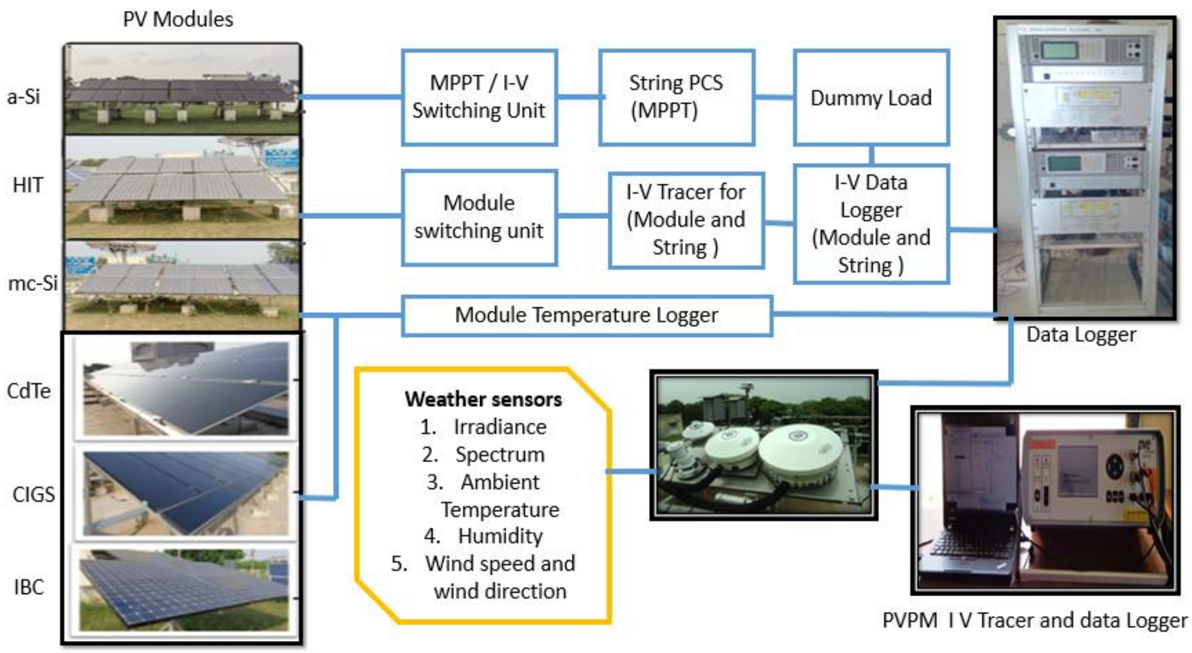


Figure 3.8 Photograph of the PV module outdoor test bed used for collecting data

Table 3.1 Total number of module for different technologies with series and parallel combinations.

Technologies	Modules configuration	Open circuit Voltage $\boldsymbol{V_{\mathrm{OC}}}(\mathbf{V})$	Short circuit current $\boldsymbol{I_{\mathrm{SC}}}(\mathbf{A})$	Maximum power $\boldsymbol{P_{\max}}(\mathbf{W})$	Voltage at maximum power $\boldsymbol{V_{\mathrm{mp}}}(\mathbf{V})$	Current at maximum power $\boldsymbol{I_{\mathrm{mp}}}(\mathbf{A})$
a-Si	4 series 4 parallel	367.2	5.6	1200	268.0	4.4
HIT	4 series 2 parallel	294.4	7.5	1680	238.8	7.0
mc-Si	10 series	256.0	8.4	1600	212.8	7.5
CdTe .	10 series 4 parallel	608.0	7.52	3200	485.0	1.65
CIGS	10 series 1 parallel	552.0	3.32	1200	427.0	2.81
IBC	10 series 1 parallel	649.0	6.46	1640	547.0	5.98

Table 3.2 Specifications of individual modules used in the test bed under STC

Technologies	V_{OC}(V)	I_{SC}(A)	Fill factor (FF)	P_{max}(W)
a-Si	91.8	1.4	0.64	75
HIT	73.6	3.7	0.78	210
mc-Si	25.6	8.4	0.74	160
CdTe	60.8	1.88	0.55	80
CIGS	55.2	3.32	0.65	120
IBC	64.9	6.46	0.78	327

Table 3.3 Physical dimensions and weight of various module technologies

PV Technology	Company	Width (mm)	Height (mm)	Depth (mm)	Weight (Kg)
a-Si	Kaneka	1008	1210	40	18.3
HIT	Panasonic	862	1630	35	26
mc-Si	Sharp	994	1318	46	15.5
CdTe	First Solar	600	1200	7	12
CIGS	Stion	655	1675	35	16.8
IBC	SunPower	1046	1559	46	18.6

Table 3.4 PV module parameters of six technologies modules

PV Technology	Company	Voltage Temp. Coefficient (mV/K)	Current Temp. Coefficient (mA/K)	Power Temp. Coefficient (%/K)	Maximum System Voltage (V)
a-Si	Kaneka	-279.99	1.05	-0.14	600
HIT	Panasonic	-129	1.64	-0.3	1000
mC-Si	Sharp	-97.55	1.71	-0.46	1000
CdTe	First Solar	-152.5	0.79	-0.25	1000
CIGS	Stion	-182.16	0.03	-0.39	1000
IBC	SunPower	-176.6	3.5	-0.38	1000

Figure 3.9 shows the schematics of a-Si, HIT, and mc-Si technologies PV test bed arrays, which demonstrate the series and parallel connections of modules in each test bed. One sample module was kept open circuit in each test bed (see Figure 3.9), and another sample module was linked to the I-V tracer (Kernel System, PVC01802) to measure I-V data every 10 minutes. These sample modules (labelled with the letter 'O') were kept in open circuit to conduct a comparative degradation study with the PV array, which was always kept under load. The a-Si test bed had a capacity of 1.2 kWp and was made up of sixteen 75 Wp single junction a-Si modules. The a-Si modules were strung together in four strings, each string containing four modules. The HIT test bed had a capacity of 1.68 kWp and was made up of eight 210 Wp modules. These HIT modules were strung together in two strings, each consisting of four modules. The mc-Si test bed had a capacity of 1.6 kWp and was made up of ten 160 Wp series connected modules.

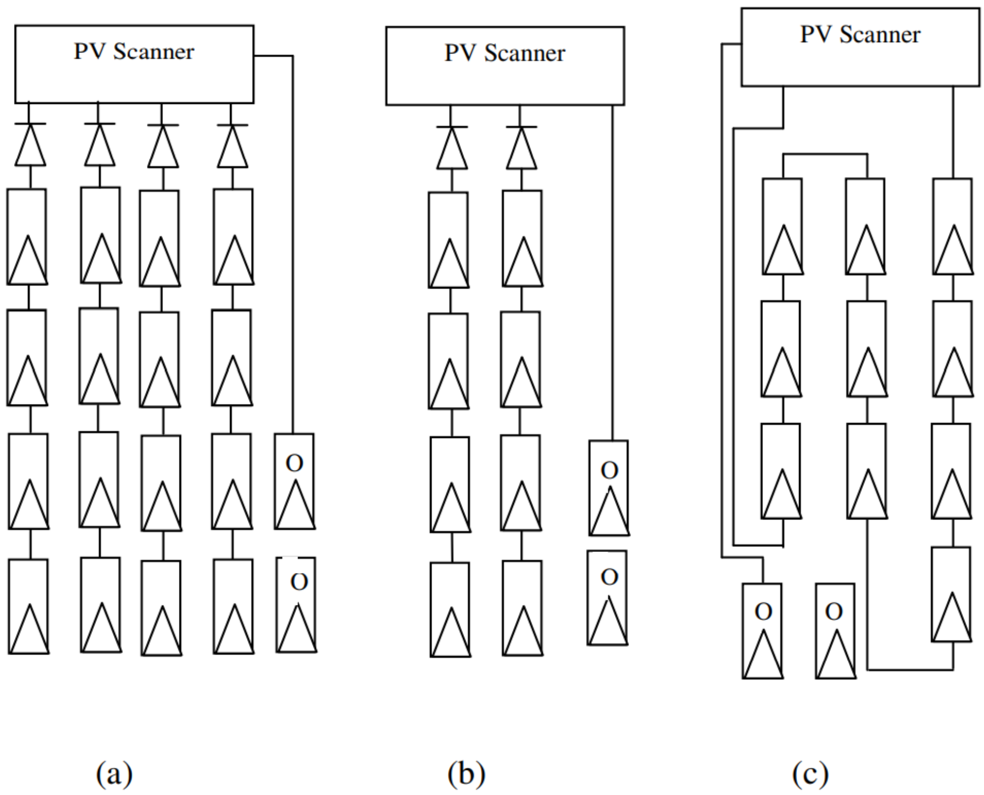


Figure 3.9 Schematic of a PV test bed (a) a-Si (b) HIT (c) mc-Si

The last three technologies PVPM is tied to CdTe, CIGS, and IBC. An array analyzer, an I–V Scanner, and a multiplexer have been placed as part of the test bed to measure the electrical parameters. Except for when I–V measurements were taken, SPV arrays were kept under load. This I-V scanner has been programmed to record I-V characteristic data for each SPV technology every 10 minutes, as well as the electrical parameters short-circuit current (I_{SC}), open-circuit voltage (V_{OC}), maximum power point current (I_{mp}), and maximum power point voltage (V_{mp}) in the data logger. For the analysis of CdTe technology, forty modules are used: ten in series and four in parallel. Ten modules are connected in series and one module is connected in parallel for CIGS, and five modules are connected in series and one module is connected in parallel for IBC.

Figure 3.10 I-V Tracer and data stored in PC

3.6 Weather Station and PV Instrumentation

Outdoor PV array, weather station, data recorder with PV array analyser, and accompanying software for sensing, monitoring, retrieving, storing, and networking for transmission and analysis make up a PV test bed. These components have been used to design and plan PV test beds. An I-V scanner, an array analyzer, and a multiplexer were installed to measure the maximum power generated by PV test beds. At the test bed site, a comprehensive weather station was installed, which was used to measure and record horizontal and in-plane solar radiation, the solar spectrum, ambient temperature, humidity, wind speed, and wind direction. A thermopile-based pyranometer was used to monitor solar radiation on the horizontal surface and at the tilt of PV modules. It had a sturdy brass shell that allowed it to be used in outdoor settings. At a height of roughly 3 m, a four-blade helicoid propeller type wind sensor was utilised to monitor wind speed. It also contains a durable and lightweight vane for measuring wind direction, with a precise potentiometer sensing the vane angle. Pt100 temperature sensor was used to determine the ambient temperature. A data logger has recorded weather parameters (Campbell Scientific, CR-1000). T-type thermocouples were used to measure the temperature of all of the technology modules (calibrated by Kernel System). Table

3-4 lists the descriptions and specifications of the equipment utilised in the weather station. Figure 3.11 shows a weather station and PV module measuring system schematic. The behavior of the modules under low irradiance conditions was studied by taking into account the change in module efficiency throughout the course of the day. The efficiency of each module was measured under varied irradiance up to 1000 W/m^2 at 25 °C using a class AAA solar simulator in order to incorporate the varying efficiency effect under different illumination in the model. The measurements were carried out according to IEC 60891 standards at a laboratory that was accredited by the National Accreditation Board for Testing and Calibration Laboratories according to standard IEC 17025 (NABL).

Table 3.5 Description of weather station instruments and specification

Instrument Name	Resolution	Company/ Make	Function
Pyranometer MS-802	10 W/m²	EKO Instruments Co., Ltd.	Solar radiation measurement on the module (tilt) and horizontal surface with 305-2800nm wavelength range
MS-710 and MS-712 Spectroradiometer	0.2 nm	EKO Instruments Co., Ltd.	Spectral distribution of the solar radiation measurement
Wind Sensor 05103	0.3 m/s, 3°	CLIMATEC, INC.(Young)	Wind speed and direction measurement
Humidity and temperature sensor HMP 155	1.7 % for RH, 0.2 °C for temperature	Vaisala KK	Relative humidity and ambient temperature measurement
PVPM IV curve analyzer	Resolution 0.01V - 0.25V, 0.005A – 0.01A, Accuracy of the a/d converter 0.08% of FSR±1 LSB	PVE Photovoltaik Engineering	Characterize the I-V-curve of PV modules and strings

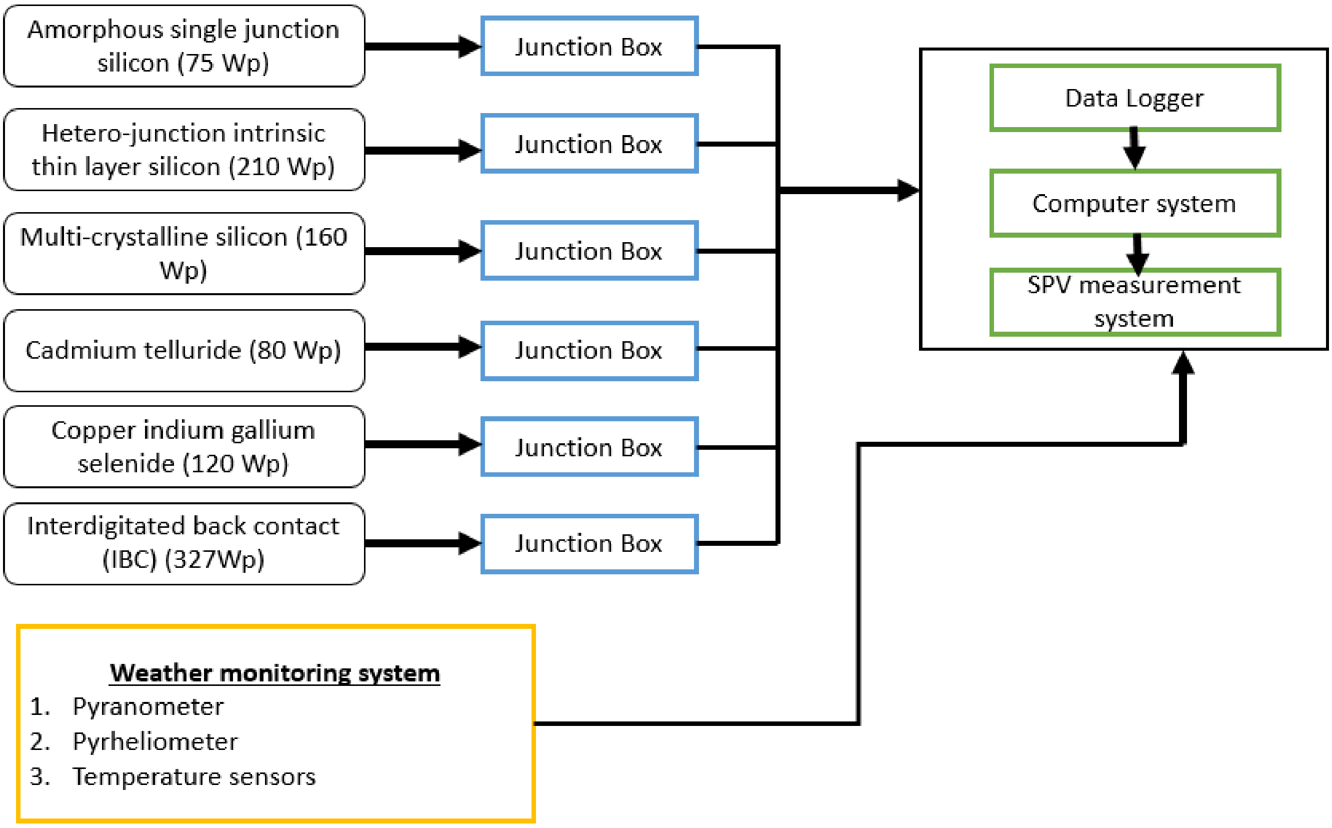


Figure 3.11 Schematic of weather station and PV module measurement system

3.6.1 Weather Station Instrumentation

Weather station should be capable of measuring all environment parameters that affect PV modules performance. These include sensors (shown in Figure 3.12 and Figure 3.13) to measure solar radiation on module surface (tilt), horizontal (global), direct normal irradiance (DNI) ultraviolet (UV) intensity, solar spectrum distribution, ambient temperature, relative humidity (RH), dew point, atmospheric pressure and wind speed and direction.

(a) (b) (c) (d)

Figure 3.12 (a) Global, (b) DNI, (c) Tilt with Spectroradiometer and (d) UV Radiation measurements

The monitoring rate is adjusted to record slow variations in the weather conditions. The solar radiation data is sufficient to correlate the power and energy generation, while other parameters like spectrum, etc. are considered necessary to understand the process of the generation and growth of a defect or degradation/ failure.

(a) (b) (c)

Figure 3.13 (a) Wind speed and direction (b) RH and Due Point, (c) Atmospheric pressure measurements

3.6.2 PV Instrumentation

The important measurements to estimate PV array parameters are $V_{\mathrm{OC}}, I_{\mathrm{SC}}, P_{\max}, FF, R_{\mathrm{sh}}$ and R_s. Along with these parameters, the instrument scans complete I-V curve at every preselected interval. These measurements are needed to estimate the energy yields for a day. During the time interval between scans, the array operates at maximum power point, which should be within the measurement limits of the PV scanner or analyser used in the system. Ideally, it is preferred to have one I-V scanner for each technologies array, which is an expensive option, therefore only one I-V scanner and a multiplexer was used for the task. In such a case however, the I-V measurement of individual PV module within the array is restricted. The measurement of I-V curve for individual modules is needed to understand the degradation rate of a particular module in the array as well as the positional dependence of degradation in PV modules. Three I-V scanners for measuring the I-V characteristics of three technologies modules is shown at Figure 3.14.

Figure 3.14 Three I-V Scanners, one for each technologies to measure I-V measurements

Every ten minutes, the weather data was captured. Each PV module test bed's I-V parameters, as well as its temperature, were measured and recorded once every ten minutes. Except for when I-V characteristics were measured, PV arrays were kept under load.

IV CURVE ANALYZER

PV-KLA Multiplexing system for I-V Curve measurement of PV modules

PV-KLA developed PV-KLA-MUX, a system for automatic I-V curve measuring of many PV modules, based on our successful I-V curve analyser. The PV-KLA MUX is typically used to gather I-V curves under various natural settings in order to determine behaviour not just under STC but also in natural conditions, and therefore to compare different PV module types. To determine the output performance of PV modules in natural sunlight, their I-V curves must be measured on a regular basis under all potential weather situations. PVKLA MUX, our multiplexing system, is the appropriate answer for practically every climatic zone. The modules, the electronic loads (passive or active), and the meteorological sensors are the main components, allowing for a variety of configurations. Since PV-KLA combines a passive load with high-speed data acquisition, it is possible to measure various types of modules with the same multiplexing system: crystalline modules, thin film modules, and even single cells are all possible with our Zero-Volt option, which measures from -0.3V to the test samples' open-circuit voltage. The PV analyzer cabinet is designed to withstand both low and high temperatures, and it usually comes with a stainless steel canopy to shield it from direct sunlight. Temperature-controlled fans, as well as cooling and heating aggregates, are also included. Robustness combined with accuracy results in a top-of-the-line piece of equipment for all PV module testing facilities.

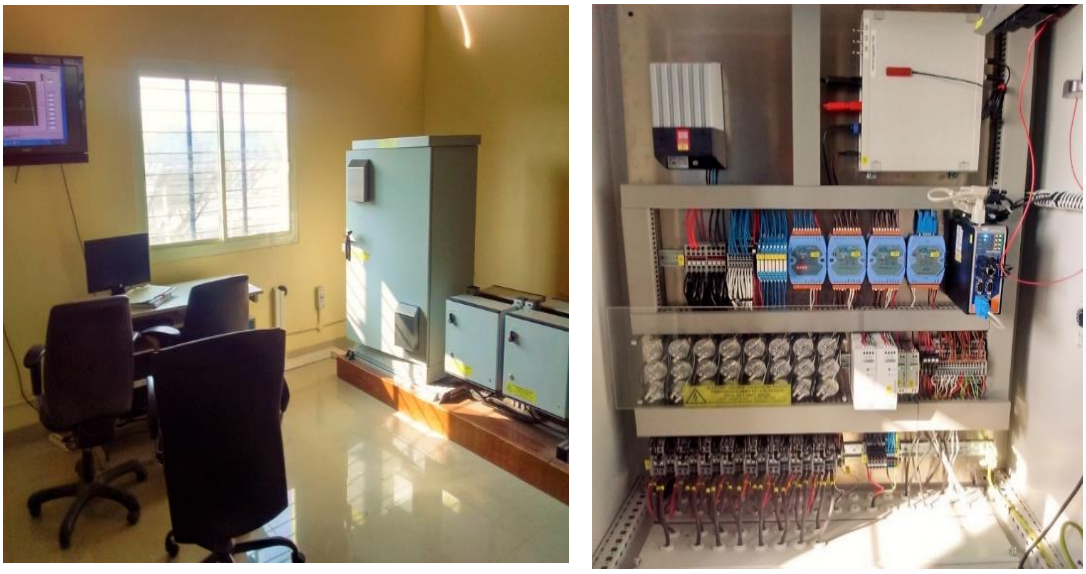


Figure 3.15 PV-KLA Multiplexing system for I-V curve measurement set up.

PV-KLA I-V Curve Analyser for PV modules

In research and industry, the I-V curve analyser for photovoltaic PV-KLA can be utilised on a variety of terms for I-V curve tracing of PV modules and generators. Because of its versatility, it can be utilised for both indoor and outdoor experiments. At German and international manufacturer sites and research centres, several devices are in use. Using the PVK software, the PV-KLA may be controlled directly and easily via a PC's communication port. A capacitive load is used to trace the I-V curve of PV generators. The device employs only one capacitor to work with a wide range of PV generators, eliminating the need to swap out hardware. Only software is used to optimise. At the same time, all four channels (voltage, current, irradiance, and temperature) are sampled. One voltage-current-irradiance-temperature value can be sampled at a maximum rate of 50 (100) kHz. The battery-powered equipment can be used for inside laboratory tests as well as portable outdoor experiments. The device's large memory for each I-V curve, high precision, and fast sampling rates, combined with irradiance and temperature monitoring in the standard version, allow it to take high-quality curves. With 1 Hz, meteorological sensors are sampled and shown. The PV-KLA can be adapted for other uses with optional customised adaptors. The PV-KLA meets the requirements of the IEC 60904-1 standard and can be calibrated with approved measuring systems. The meteorology adds numerous more channels for meteorological sensors to use (Pt100 sensors, wind, Pyranometer). The cell adapter allows to measure the I-V curve of individual PV cells. The user-friendly control software PVK is written in English and displays all key I-V curve parameters, including the curve as visuals, in a single measuring window. The mouse or keyboard can be used to control it. Long-term observations with user-defined time intervals, as well as temperature coefficient calculations for parameters such as open-circuit voltage, short-circuit current, or power within the maximum power-point, are all feasible (MPP). There is also a multiplexer for numerous PV modules. As seen in Figure 3.15, it is operated by a computer.

3.6.3 Data Logging Strategy

The software consists of programs for sensing weather, estimating, averaging, integrating and tabulating weather parameters. Embedded device collects all data from weather sensors, forms tables in data base using MySQL freeware database package. It is possible to create CSV files containing individual table, as well as entire database. The data can be collected over large time and for a specific period also. Software also includes programs for I-V measurements of PV arrays and modules against time. This operates only during the sunny hours of a day. The heart of the data logging facility is the timestamp facility, which helps user to view and compare I-V curves over selected time period for different technologies modules. This is achieved by using indexing feature of database tables, so that the insertion and retrieval of data can be fast, even if the span of data is between years. It is estimated that for a day, about 230KB is required for weather data and about 3MB is required for storing PV monitoring data for one technologies.

3.7 Application of Extracted Data

The data extracted from the test bed and weather station with the help of data logging strategy and associated instrumentation has been used in this thesis work. The data related with the study mentioned in thesis chapters were applied for analysing seasonal spectral variations, wind effect on module temperature, and distribution of frequency of occurrence at the site. The data has also been applied for parameter extraction of PV module temperature model.

3.8 Studies performed.

The major parameter for this study are as follows:

3.8.1 Energy Yield and Performance Ratio (PR): Meteorological data as well as technical features of the PV power plant under consideration are essential for determining the energy production of photovoltaic (PV) systems. The electric output may be computed using this data, taking into account the plane-of-array irradiation, nominal capacity, and PV system Performance Ratio (PR).

3.8.2 Most frequent condition (MFC) study: A performance evaluation technique employing most frequent circumstances (MFC) for accurate design of photovoltaic systems, based on energy rating and site-specific variables, was used to examine several SPV technologies.

3.8.3 Impact of weather parameters

There is various parameters which are affecting the power performance of solar power plant. The key parameters are irradiance, temperature, wind speed and direction, soiling and humidity which is shown in table 3.6.

Table 3.6 Environment Parameter and their impact

S.no	Environment Parameter	Impact on PV Modules and consequences
1	Irradiance	Discoloration (yellowing), reduced power output
		Moisture ingress
		Degradation on cell material, reduced power output.
2	Temperature	Different thermal expansion coefficients
		Opening of soldering joints due to unequal thermal expansion
		Degradation of electrical parameters with temperature, hotspot and burn mark on the cell
		Cell cracks with the help of Electroluminescence (EL).
		Degradation of solar panels
3	Module Current	Corrosion/ageing of cell and interconnects inside the modules
4	Wind	Mechanical fatigues of various types
		Damage in the underlying structure due to vibrations
5	Soiling	Reduction in the short circuit current of the modules
		Shading effect, which may lead to formation of hotspots.
6	Humidity	Moisture ingress.

3.8.4 Degradation and reliability study

Several issues such as broken interconnect, broken cell, solder, junction box failure, delamination, corrosion, Hotspot, bypass diode etc. affect the degradation of solar modules in their life time cycle. These issues and their consequences have been displayed in table 3.7.

Table 3.7 Degradation mechanism and corresponding stress factors

Degradation mechanism	Stress factor				
	High temperature	Moisture	Thermal cycling	UV	High voltage
Broken interconnect	YES	YES			YES
Broken cell	YES				YES
Solder bond failures	YES	YES	YES		YES
Junction box failure	YES	YES			
Corrosion	YES	YES			YES
Delamination of encapsulant	YES	YES	YES	YES	YES
Encapsulant discoloration	YES			YES	
Hot spots	YES				
Electrochemical corrosion of TCO	YES	YES			YES
Ground fault		YES			YES
Bypass diode failures	YES		YES		

3.8.5 Prediction and forecasting analysis.

Artificial neural networks (ANN)

An artificial neural network (ANN) is a massively parallel-distributed processor that is similar to the human brain in two ways: knowledge is acquired through a learning process, and interneuron connection strengths, known as synaptic weights, are used to store knowledge [11]. A neural network is trained for a desired task by adjusting these weights between the elements of interest. A typical flowchart of ANN working is given in Figure 3.16. As shown in the figure, the network is trained by adjusting the weights until the neural output matches the target data and we then get the desired mathematical relation. ANN has been widely used in various energy sectors to predict the performance of energy devices including water heaters, passive solar buildings, air conditioning in bus, room storage heater and tariff forecasting and energy management of any area [12, 13]

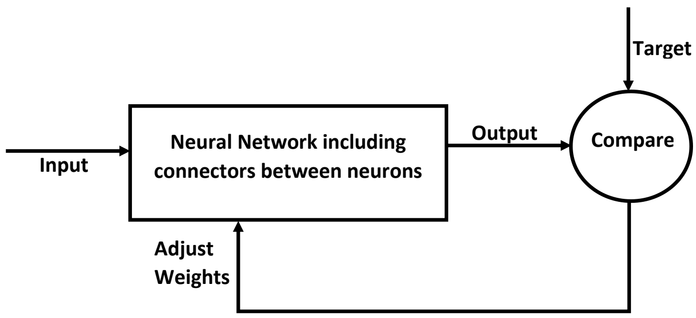


Figure 3.16 Flowchart of Neural Network Analysis

3.8.6 Electroluminescence imaging (EL imaging) study

Input energy is converted into photons in electroluminescence imaging (EL imaging). The input energy for electroluminescence and photoluminescence can be in the form of electrons or photons, respectively. Because the emission intensity is related to both carrier lifetime and current density, electroluminescence (EL) imaging is the most often utilised method for failure investigation. Electroluminescence can easily detect poor connections and non-uniform current. Photoluminescence (PL) imaging has recently been introduced for failure analysis applications, and electroluminescence (EL) imaging is useful in distinguishing between increased series resistance and reduced parallel resistance. **Infrared/thermal imaging**

Infrared/thermal imaging is another technique that is widely used to locate the degradation/failure point in a field-exposed module. Because of the joule heating impact caused by weak connections, shunted cells, and short circuits, this technique makes use of the concept of localized heat generation. This occurs because the cells that produce less current than the other cells in the series get reverse biased and begin to behave like resistors, dissipating heat. During thermal imaging, the dissipated heat causes a temperature gradient, which appears as bright spots. A camera sensitive to infrared light in the 3–15 µm range is employed in this technique.

3.9 Modelling Software

Various simulation software such as PVSYST, PVSOL, SAM etc. are used to perform the investigation. Matlab's neural network toolbox (nntool) is used for prediction and forecasting analysis.

3.9.1 PVSYST 7.0

It is a software application that allows the researcher to research, size, and analyse full PV systems. It has access to large meteo and PV systems components databases, as well as general solar energy tools, and takes are of grid-connected, stand-alone, pumping, and DC-grid (public transportation) PV systems. Architects, engineers, and researchers will benefit from this software.

The system yield evaluations are produced extremely fast in monthly numbers, using only a few broad system features or parameters, without identifying real system components (project presizing). It also provides a preliminary estimate of how much the system will cost. This tool can be used to calculate the required PV power and battery capacity for stand-alone systems based on the load profile and the likelihood that the user will be dissatisfied ("Loss of Load" LOL probability, or equivalently the desired "solar fraction"). Given water requirements and a pumping depth, as well as certain general technical choices, this tool calculates the pump power and PV array size required for pumping systems. In the case of stand-alone systems, this sizing can be done based on a probability that the water needs will not be satisfied over the course of the year. Figure 3.17.

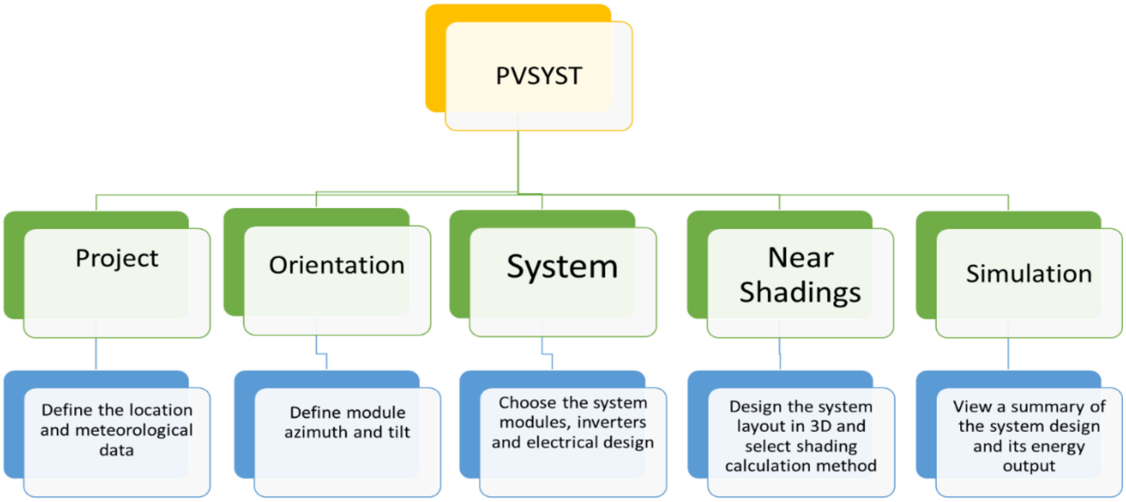


Figure 3.17 Flow chart showing different steps of modelling through PVSYST

Full system design in PVSYST is carried out by employing hourly simulations. In this, the user can perform different system simulation runs and compare them within the scope of a "project." The user must select the exact system components as well as the plane orientation (with the option of tracking planes or shed mounting). Given a chosen inverter model, battery pack, or pump, the user is assisted in designing the PV array (number of PV modules in series and parallel). The user can then select more detailed settings and investigate finer features such as thermal behaviour, wiring, module quality, mismatch and incidence angle losses, horizon (far shading), or partial shadings of close objects on the array, and so on in a second phase. Several dozens of simulation variables are included in the results, which can be shown in monthly, daily, or hourly values and even exported to other software. The "Loss Diagram" is especially effective for spotting the design flaws in a system. For each simulation run, an engineer report may be printed, which includes all simulation parameters as well as the major outcomes. Real component pricing, any additional costs, and investment conditions can all be used to produce a detailed economic analysis. By default, the grid in grid-connected systems acts as an unlimited consumer. This includes load profiles for self-consumption, grid storage, peak shaving, and weak islanding. The installation of MV and HV transformers, as well as grid limits, allows the user to control the system until it reaches the injection point.

PVSYST has access to large meteo databases. The creation and management of geographical sites, generation of synthetic hourly data files, visualization of hourly meteorological data, the comparison of meteorological data, and the import of meteorological data from several predefined sources or custom files are all done in these databases. Database management of manufacturers and PV components, such as PV modules, inverters, regulators, generators, pumps, and so on, is also done in these databases.

PVSYST provides a suite of utility tools for displaying meteorological data or solar geometry parameters, irradiance under a clear day model, PV-array behaviour under partial shadings or module mismatch, and optimising tools for orientation or voltage, among other things. These tools aid in the round-the-clock monitoring of PV systems as well as the import of measured data (in virtually any ASCII format) into tables and graphs of actual performance and close comparisons with simulated variables. These tools are useful not only for analysing the system's actual operational parameters, but also for detecting extremely slight abnormalities. The following diagram (Figure 3.17) depicts PVSYST's overall process flow when working with solar energy systems.

3.9.2 PVSOL

PVSOL is an industry standard software for developing and simulating photovoltaic systems of various types. It may be used to create everything from small rooftop systems with a few modules to medium-sized commercial roof systems to enormous solar parks. PV*SOL premium is distinguished by its unique 3D visualisation. All typical types of systems may be shown in 3D, whether roof-integrated or roof-mounted, on small angled roofs, big industrial halls, or open areas - with up to 7,500 installed modules or up to 10,000 roof-parallel modules and shading can be calculated using 3D objects. This allows for the highest level of forecasting accuracy, as a realistic representation of the shading from surrounding objects is required for an accurate income computation. PV*SOL premium also has a variety of other design types. One can select the type of design that best suits the PV project, and the software will generate a full report on the design's performance. The current feed-in tariffs are already stored in the database for economic efficiency calculations. With the information on system expenses, a complete and meaningful economic analysis of the system for the next 20 years can be obtained. Figure 3.18 depicts the many modelling phases in PVSOL. Salient features of the PVSOL software are:

- **Simple configuration:** Determination of the best inverter setup is done automatically. Manual configuration adaptation is sophisticatedly supported.

- **Several methods to access PV module locations.** Using a snapshot of the house, it is possible to determine the number of modules and see the module surface. In a graphical 2D roof view, automatic module attachment on every roof type is possible.
- **Optimal outcome evaluation and presentation.** Grid-connected PV system yields are simulated hourly. A detailed economic projection with key elements such as yield payback time is provided.
- **Up to date.** The producers update their databases on a regular basis (PV modules inverters, battery inverters).
- **Optimal user assistance.** Entry checking eliminates any dimensioning errors. Favorites make it simple to choose products (batteries, PV modules, inverters, and battery inverters). PV system planning including consumption, net metering, and battery storage AC Losses Calculation Losses in DC and string

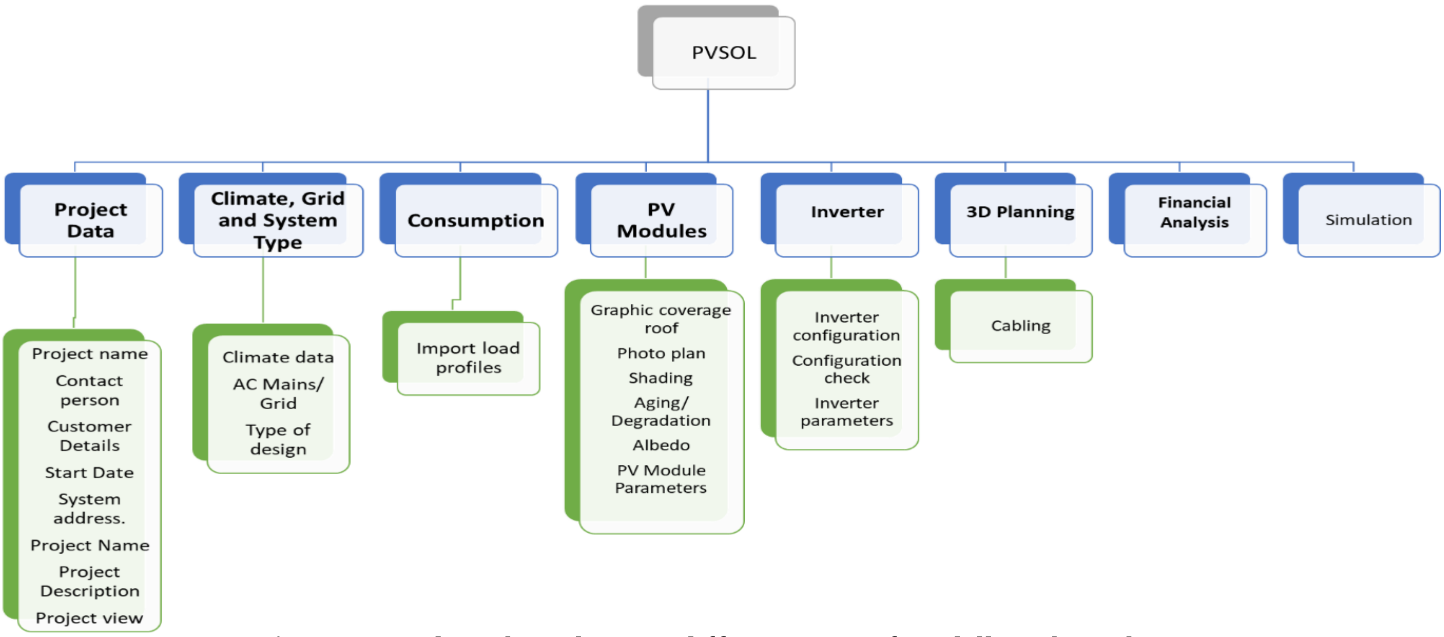


Figure 3.18 Flow chart showing different steps of modelling through PVSOL.

3.9.3 SAM (System advisor model)

Photovoltaic systems with optional battery storage, concentrating solar power, industrial process heat, solar water heating, wind, geothermal, biomass, and traditional power systems that either deliver electricity directly to the power grid or interact with the electric load of a grid-connected building or facility are all covered by SAM's performance models. Off-grid power systems and hybrid power systems with multiple power generation sources are not modelled by SAM. The financial models are for projects that buy or sell electricity at retail rates (both residential and commercial), or sell electricity at a price set in a power purchase agreement (PPA). SAM can mimic a wide range of projects, from modest rooftop photovoltaic systems to big concentrating solar power generation plants and wind farms. Because SAM is an open source project, anyone can access its source code. Researchers can examine the code to learn more about the model algorithms, and software developers can submit their own models and improvements to the project. Model algorithms reference guides are also available for download from the SAM website (Figure 3.19). SAM's performance models calculate a power system's electric output by time step, resulting in a set of time series data that represents the system's electricity generation over a single year. The simulation time step is determined by the data in the weather file's temporal resolution, which might be hourly or sub-hourly. One can dig further into the system's performance characteristics by looking at tables and graphs of time series performance data, or utilize performance indicators like the system's total annual production and capacity factor for a more broad assessment. Performance models for the following technologies are included in SAM. SAM have also design the Photovoltaic (PV) module with electric battery storage, High concentration PV CSP trough with a parabolic shape Tower for CSP power (molten salt and direct steam), CSP linear Fresnel lens, Integrated solar mixed cycle with CSP , Sterling CSP dish, Linear direct steam and a parabolic trough for process heat, Thermodynamics as we know it (a simple heat rate model) Residential and commercial buildings can benefit from solar water heating.

Figure 3.19 Overview of simulation report through SAM

3.9.4 Prediction of module temperature with artificial neural network scheme

The prediction of temperature of PV modules in different climatic conditions have been done using Matlab's neural network toolbox (nntool). The input data is acquired from the National Institute of Solar Energy (NISE) in Gurugram, India, in order to develop the model. The PV system used a combination of four series and four parallel 75-watt amorphous-silicon modules for a total of 1200 Watts of net output. Using the aforesaid setup, yearly data for 2010 was recorded, which included a variety of meteorological characteristics. The data was sampled every 10 minutes and averaged for every hour. The data was recorded for five input and one output parameters: solar irradiance (I_{rr}), relative humidity (RH), wind speed (WindSpd), wind direction (WindDir) and ambient temperature (T_{ambient}). The one output parameter was the module temperature (T_{module}), which is the target temperature (or the output) for neural network model. In the model, solar irradiance is measured in watt/m^2; wind speed is measured in m/s; wind direction has been taken in North azimuth degree (°); the temperatures (ambient and target) are measured in °C, and relative humidity is measured in percentage (%) from 0 to 100%.

Neural network developed using single perceptron model, was solved using neural network toolbox of Matlab® R2017b (nntool). The data obtained from NISE consisted of several inputs and the target. The objective was to obtain a mathematical relationship between the module target temperature and weather- based conditions (Irradiance, humidity, wind speed, wind direction and ambient temperature), in form an equation given below

$$\boldsymbol{T_{\mathrm{module}}} = (\boldsymbol{w_1} * \boldsymbol{I_{\mathrm{rr}}} + \boldsymbol{w_2} * \mathbf{RH} + \boldsymbol{w_3} * \mathbf{WindSpd} + \boldsymbol{w_4} * \mathbf{WindDirec} + \boldsymbol{w_5} * \boldsymbol{T_{\mathrm{ambient}}}) + \mathbf{constant}$$

For the full year of 2010, the data consisted of points being sampled and recorded every 10 minutes (January- December). As a result, the data count was massive. The data was, therefore, separated into months and averaged. It was done to make modelling our neural network easier and less error-prone. The network was divided into three segments, as is customary in an ANN system: training set, validation set, and testing set. The training set is used to fine-tune the neural network's weights. To avoid over-fitting, a validation set is utilised. With this data set, we're not altering the network's weights; instead, we're ensuring that any improvement in accuracy over the training data set is also an increase in accuracy over a data set that the network hasn't seen before, or at least hasn't been trained on (i.e. validation data set). If the accuracy of the training data set improves but the accuracy of the validation data set remains the same or declines, the neural network is over fitted and training should be stopped. The testing set is only used to test the final solution and check the network's true predictive power.

Based on a comparison of the output and the target, the network was changed until the network output matched the target. We kept training and developing a relationship between the target and the output until the ANN training plot shows high R (coefficient of correlations) values. To acquire the best result, we also adjust parameters like epochs and aim. In order to confirm the effectiveness of our model, a linear regression curve was generated to compare the neural output temperatures with the target module temperature.

3.10 Degradation analysis

The capacity to precisely estimate power delivery over a specific time period is critical to the photovoltaic (PV) industry's growth. The efficiency with which sunlight is turned into power, as well as how the efficiency of power production (reliability) fluctuates over time, are two major drivers. The degradation rate is used to measure the rate of power decline over time: a higher degradation rate immediately corresponds to less power production. The rate of degradation of photovoltaic (PV) modules is determined by module technology, manufacturing, and environmental factors. . The characterization of photovoltaic (PV) module degradation rates is crucial for ensuring their current lifetime and the economic viability of PV systems. The increasing use of PV systems in India necessitates degradation study. We investigated the degradation of three distinct module technologies in a variety of environmental settings over a five-year period of outside exposure. Based on maximum power output and PR data, the degradation rates of solar modules is evaluated. Degradation rate is calculated with the help of real field data, and module's maximum output power. The initial $P_{\max}$ is noted at the time when module is installed in outdoor conditions. After deploying the module in outdoor conditions for the desired time, final $P_{\max}$ is estimated. Degradation rate is then calculated by finding the ratio of the difference between initial maximum power and final maximum power to initial maximum power.

The lowest degradation happens in a-Si module technology (0.85%), followed by m-Si module (0.95%); highest degradation rate has been observed to be 1.1 % in case of HIT module technology in composite climatic conditions.

Table 3.8 Degradation Analysis of a-Si, mc-Si and HIT technology

Technology	Method	Degradation Rate %	Location
a- Si	PR based	0.85	NISE Gurugram
m- Si		0.95	
HIT		1.1	

The percentage degradation has been calculated by the following formula

$$\text{Percentage of degradation } = \frac{\text{Initial } P_{\max} - \text{Final } P_{\max}}{\text{Initial } P_{\max}} * 100$$

CHAPTER 4

RESULTS AND DISCUSSION

4.0 Introduction

In this Chapter, the results of the simulated scenarios and the optimization process are introduced. Section 4.1and 4.2 covers the Performance of Cadmium Telluride & Micromorph based thin film photovoltaic system in composite climate. Subsequently the Performance of HIT module in different climatic condition in India has been discussed. Sections 4.3 covers the performance analysis of different PV module technologies for different climatic conditions of India. Thereafter Comparison of P50 –P90 value of different module technologies has been done in section 4.4. The last section of this chapter discusses the prediction of module temperature from weather parameters using ANN.

4.1 Performance of Cadmium Telluride & Micromorph Based Thin Film Photovoltaic Systems in composite climate

The loss analysis of CdTe and micromorph PV modules installed in composite climate of India was performed. A comprehensive module characterization with the related uncertainty analysis has been carried out by using the real electrical parameters measured at the operating field conditions. The impact of cracks in the PV module on the I-V curve has also been evaluated. In figure 4.1, schematic of 3.2 KW CdTe PV system has been given. The test bed consists of 40 modules in four parallel arrays; each array consists of ten modules connected in series. Whole system is then connected with an inverter with maximum power point tracking scheme, a data logger (for data acquisition every 10 s) and a weather station for monitoring horizontal and tilted surface irradiance, ambient temperature, wind speed and direction, relative humidity and rain humidity (see Figure 4.2).

In Figure 4.3, 8.64 kWp micromorph-based power plant along with the control room is shown. The system comprises of 8 strings having total 72 modules of 120 WP. The rated power of each module is 110 WP, each string has 9 series connected modules and 2 strings are connected in parallel combination making an array.

A power drop of 49% has been recorded in micromorph PV modules as a result of 24% reduction in the panel area due to crack defects. The performance assessment of both the technology PV modules (CdTe and micromorph) has been initially carried out over a period of one year field exposure. The role of irradiance, ambient temperature and spectral effects have been employed to quantify the corresponding losses/gain in power generation. The performance ratios of CdTe and micromorph PV modules have been found to be 0.80 and 0.65, respectively. Spectral and temperature losses up to -29.2% and -10.1%, respectively, have been recorded in the micromorph PV module. However for both PV module technologies' results are found insensitive to the irradiance effects with negligible loss of approximately -1%. Overall, the CdTe module technologies is found to be more efficient than the micromorph PV modules in composite climate.

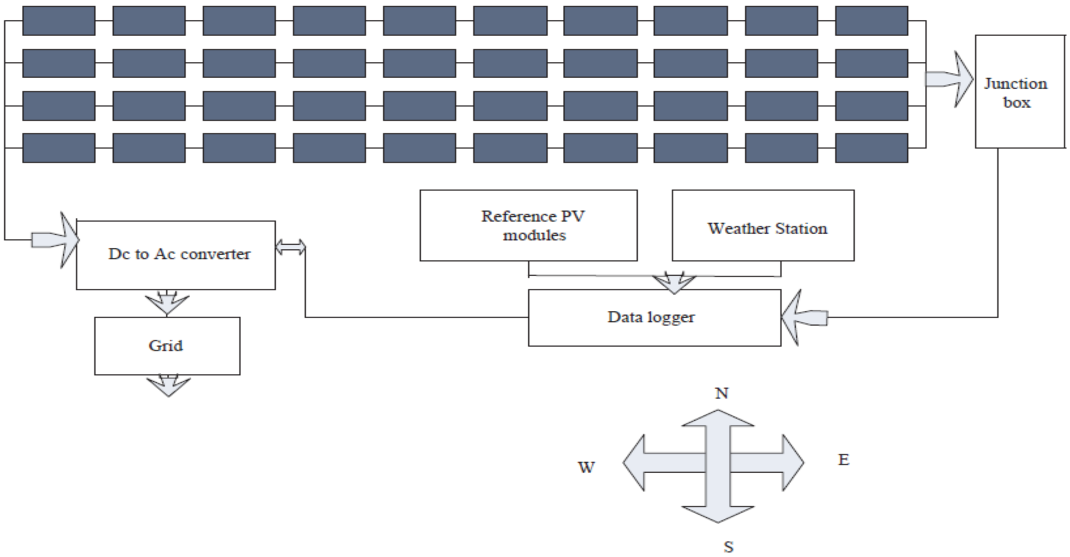


Figure. 4.1 Systematic diagram of 3.2 KW CdTe PV system

Figure. 4.2 3.2 kWp PV system with reference PV module and Pyranometer

Figure. 4.3 8.64 kWp PV Micromorph Power Plant Along With Control Room

4.1.1 CdTe and micromorph module characterization

The I-V characteristics of these PV module technologies have been recorded with the help of the PVPM2540C device. The measured I-V characteristics need some corrections due to temperature and irradiance effects. The International Standard IEC 60891 provides a procedure for correcting the real I-V curve in accordance with Eq. (1) and (2) as given below.

$$I_2 = I_1 + I_{sc}\left(\frac{G_2}{G_1} - 1\right) + \alpha(T_2 - T_1) \quad (1)$$

$$V_2 = V_1 - R_s(I_2 - I_1) - kI_2(T_2 - T_1) + \beta(T_2 - T_1) \quad (2)$$

In these equations,

I_1 , V_1 are coordinates of points on measured characteristics;

I_2, V_2 are coordinate the corresponding points on the corrected characteristics:

G_1 is the irradiance measured with the reference device

G_2 is the irradiance at the standard or other desired irradiance.

T_1 is the measured temperature of test specimen.

T_2 is the standard or other desired temperature.

I_{sc} is measured short- circuit current of the test specimen at G_1 and T_1;

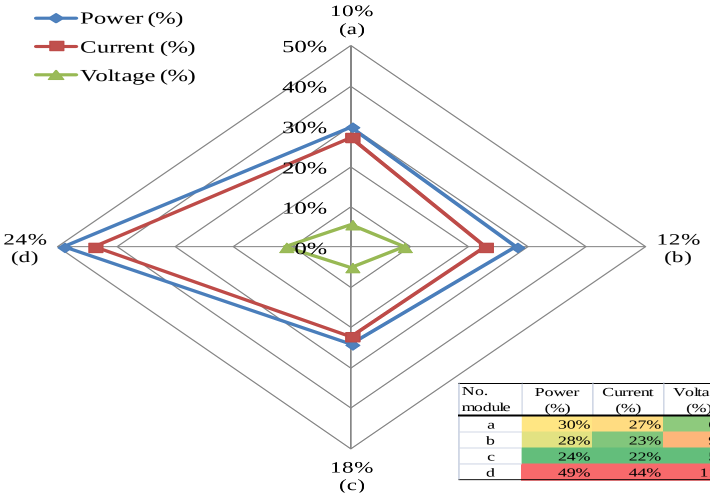
α and β are the current and voltage temperature coefficient of the test specimen in the standard or target irradiance for correction and within the temperature range of interest;

R_s is the internal series resistance of the test specimen.

k is the curve correction factor

The measured I-V curves of each PV module in real operating conditions have been translated to standard test conditions (STC) with the help of Eq. (1) and (2) in accordance with a correction procedure provided by International Standard IEC60891. The internal series resistance R_s and the curve correction factor k have been calculated using the procedure suggested by IEC60891. The stabilized power of the CdTe (78 Wp) and micromorph (110 Wp) modules has been used for the calculation in the present analysis. The temperature coefficient has been taken from the literature. The temperature coefficients of power (γ) for CdTe and micromorph modules are -0.25%/^{o}C and -0.31/^{o}C, respectively. The temperature coefficients of short circuit current (α) for CdTe and micromorph modules are 0.04%/^{o}C unit and 0.01%/^{o}C unit, respectively.

In the present analysis, the module characterization has also been performed to locate various types of visual defects in PV module, e.g. cracks, etc., which are responsible for the output power drop. In order to understand the influence of cracks in PV modules on the I-V curve, four different micro-morph PV modules have been selected with different areas of defects. Figure 4.4 shows the effect of cracks on decrease in the values of various electrical parameters measured from the defected areas of the PV panels. The PV modules with larger defected areas have significant power drop/loss. Module (a) with 10% defected area has 30% power drop, which becomes 49% for PV module (d) having 24% defected area. This is due to the inefficient production of current from a crack cell, and the fact that the flow of the current through the string interconnection ribbon is inhibited. In addition, the crack cell does not contribute to the total voltage because the junction of the solar cell is also disturbed by the crack. Such results are in accordance with the I-V characteristics. The dashed lines are the I-V curves at the maximum power point (MPP). Area under each curve represents the power at MPP (yellow lines) and at operating conditions (red lines). It is evident that module (d) with large crack area performs worst in terms of the output power drop, which is also visible from the Figure : the area under red line is smaller than the area under the yellow line. Similar considerations also apply for the remaining panels. The module (c) shows best performance in terms of power output at maximum power point condition (MPP), that means it presents the lowest power drop. Finally, in order to estimate the measuring accuracy, calibration of the reference cell (solar radiation sensor SOZ-03), data logger (Campbell Scientific CR-3000) and temperature sensor (thermocouple) is done according to the procedure established in IEC 60904-4.



No. module	Power (%)	Current (%)	Voltage (%)
a	30%	27%	6%
b	28%	23%	9%
c	24%	22%	5%
d	49%	44%	11%

Figure 4.4 Effect of cracks on electrical parameters of micromorph PV modules

Results related to the uncertainty parameters are depicted in Table 4-1. It is expected that because of the influence of solar spectrum, the measurement of current in the reference cell of the PV technologies has highest uncertainty mainly due to device (3%) and electrical parameters of the cell (3.05%). Other parameters, for instance voltage and temperature, do not have a higher uncertainty due to their sole dependence on the band gap. Furthermore, the measured and corrected values of current and voltage for CdTe and micromorph PV modules have been fitted by linear regression method. The R^2 analysis, as listed in Table 4.2, demonstrates a close agreement between measured and corrected data for CdTe technologies modules especially in term of voltage.

Table 4.1 Measurements and Uncertainty due to electrical and device specific parameters

Parameters	Uncertainty (%)
Reference Cell	3
E measure	0.3
T measure	1
T back-cell	2.5
V measure	2.64
I measure	0.04
Irradiance	1.26
Temperature	1.95
Voltage	0.21
Current	3.05

Table 4.2 R^2 for curve fitting of measured and corrected values CdTe and micromorph Modules.

Observable	R^2 for CdTe	R^2 for Micromorph
I_{sc}	0.001	0.030
V_{OC}	0.289	0.039
I_{mp}	0.016	0.056
V_{mp}	0.194	0.034
P_{m}	0.309	0.009

4.1.2 Performance evaluation of CdTe and Micromorph technologies panels

The performance ratio has been calculated based on two different irradiance conditions:

(i) G_{POA} Plane of array irradiance

(ii) $G_{\mathrm{POA,CS}}$ Plane of array irradiance in clear sky conditions only.

G_{POA} has been calculated using the solar radiation sensor SOZ-03 and T_{cell} has been calculated by attaching thermocouples on the back side of the PV modules. Results of the performance ratio for both PV systems have been presented in Figure 4.5 (a)-(d). Out of these Figure, Figure 4.5(a) and4.5 (c) show the results of PR for CdTe and micro-morph PV systems at clear sky conditions. Figure 4.5 (b) and 4.5 (d) show the results of PR for the same technologies PV panels at standard test conditions, respectively. In the case of CdTe PV system, the PR_{cs} is 0.86 whereas PR_{STC} (temperature corrected performance ratio (PR_{STC})) is 0.80. This indicates that the PR in the case of clear sky condition is marginally higher than STC value, which may be due to the fact that in clear sky conditions the spectrum range suitable for the band gap of CdTe PV module under irradiation conditions is of the order of (200 W/m^2 – 800 W/m^2). Similarly, in the case of the micromorph PV modules, PR_{cs} is 0.68 and PR_{STC} is 0.65. Furthermore, CdTe PV module shows higher performance than micro-morph PV module. The R^2 value for the linear curve fitting of PR with irradiance data has also been investigated for both technologies in clear sky conditions and at standard test conditions. In the case of CdTe PV system, R^2 for the PR_{cs} is 0.01, whereas R^2 for PR_{STC} is 0.21, whereas in the case of the micro-morph PV modules -3.79 and -2.12 are the R^2 values at CS and ST conditions. This means that the performance of CdTe system is not strictly correlated to the irradiance, unlike for the micro-morph system, which presented a stronger relationship with the solar irradiation even if the PR decreases with increasing irradiance ($R^2 < 0$). The reason for the negative value of R^2 can be found in power stabilization of the PV modules under investigation. During initial months of the outdoor exposure, the modules had higher power output, but it decreased with time due to stabilization.

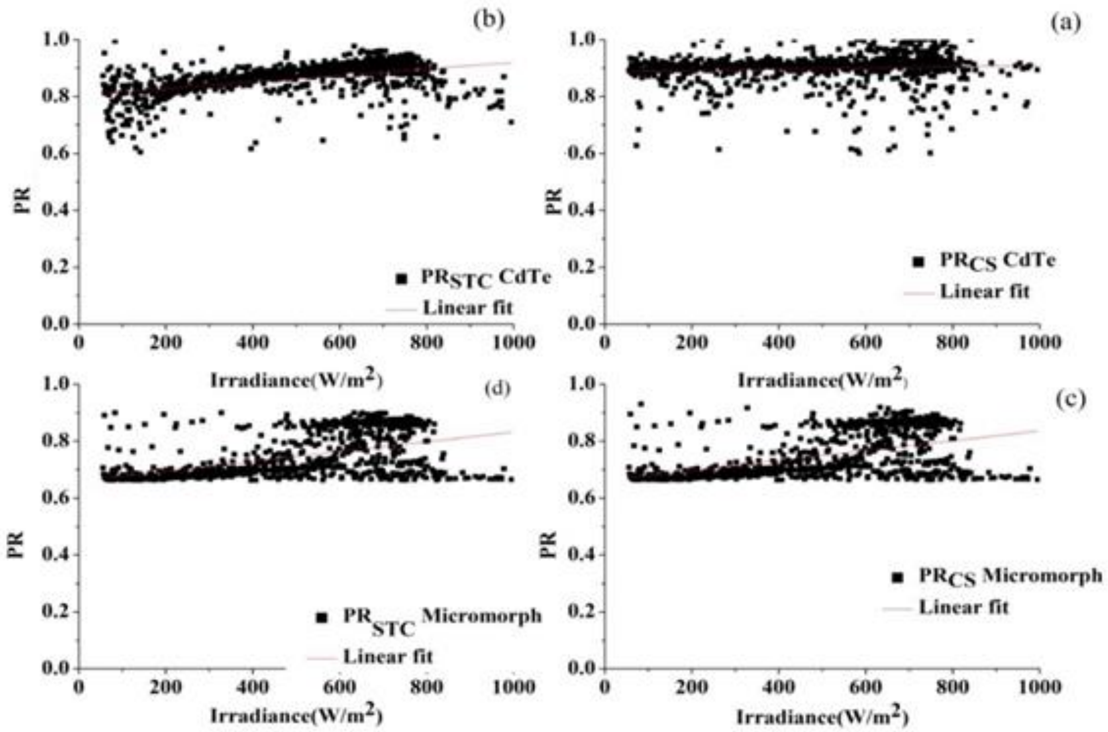


Figure 4.5 PR_{STC} and PR_{CS} for CdTe and Micromorph PV modules

In order to quantify the spectral losses, the average change in the air mass is calculated for every 17th day of the month throughout the year. It has been found to be lower early in the morning and higher at the middle of the day. The reason behind this might be due to drastic changes in the angle of incidence from morning to the evening. Spectral losses for CdTe and micro-morph PV technologies have been investigated every month during the year, and calculated for both the technologies by taking the AM values and irradiance data of Gurugram, India. As shown in Figure 4.6 for the micromorph PV technologies modules, the spectral losses vary between -29.2% and 2.4% with the highest losses during summer; other losses include thermal losses and losses due to inability of the modules to absorb higher spectrum irradiance. However, in winter it gains slightly about 2.4% due to suitable irradiance spectrum. In the case of the CdTe PV technologies, losses reach up to 5.2% in summer, which recovers slightly in winter by approximately less than 0.4%. This indicates that the CdTe technologies has the suitable band gap according to the composite climatic condition.

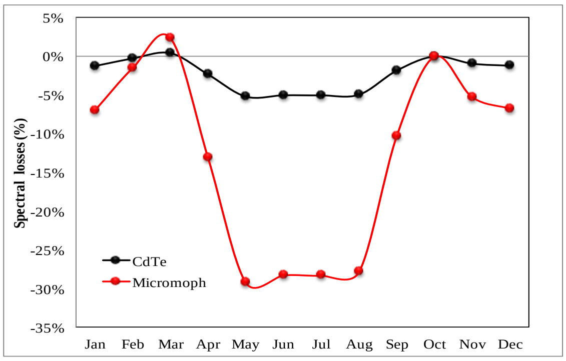


Figure 4.6 Spectral losses/gain in CdTe and Micromorph PV modules

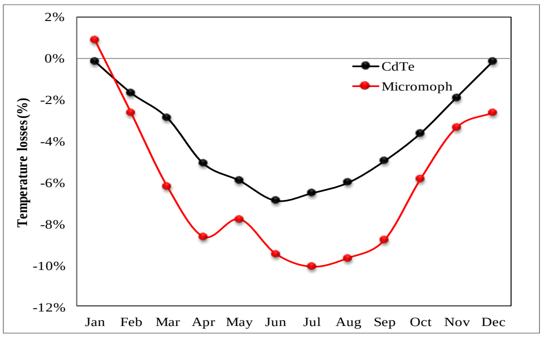


Figure 4.7 Temperature losses/gain in CdTe and Micromorph PV modules

Temperature losses for both the thin film PV technologies modules have been calculated using the real data, measured with the help of thermocouples placed at the back of the PV modules and recorded with the help of a Campbell Scientific CR-3000 data logger. As expected, the temperature losses in both the PV technologies are dominant during summer, which has also been shown in Figure 4-7. Temperature losses vary from +0.2% and - 6.9% for CdTe PV technologies and for the micromorph PV technologies, this variation is in the range -10.1% to +0.9 %. No gain in the performance has been observed for both the technologies during winter and other seasons. Temperature losses in summer mainly depend on the CdTe module temperature (71±2 ^{o}C) and micromorph module temperature (67±2 ^{o}C).

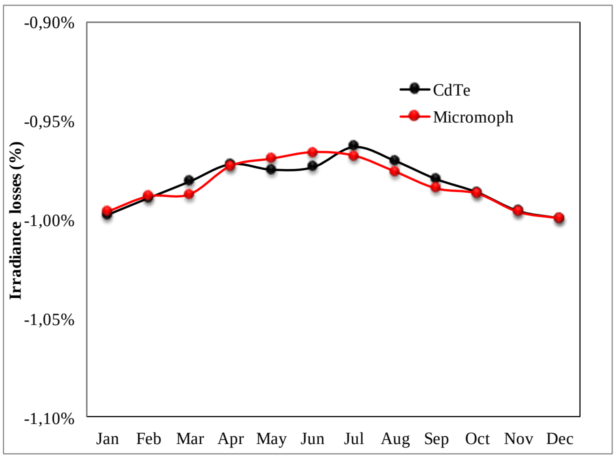


Figure 4.8 Irradiance losses/gain in CdTe and Micromorph PV modules.

Irradiance losses for both the technologies have been plotted in Figure 4.8. Both the technologies are capable of absorbing a large spectrum of irradiance (0-1000 W/m^2). These technologies have been observed to show negligible irradiance losses throughout the year: 1% irradiance loss for both CdTe and micro-morph technologies. In addition, the variation in the irradiance losses is found to be constant even in real operating conditions; the variation has been in the range -0.97 to -1%.

4.2 Performance of HIT module in different climatic condition in India

High-efficiency heterojunction with intrinsic thin-layer (HIT) technology is a highly efficient module technology, whose performance depends upon the climatic conditions. In this investigation, performance of HIT module under various climatic conditions prevailing in India have been done with the help of logged sensor data at NISE (National Institute of Solar Energy, Gurugram). Five different climatic conditions have been considered: hot and humid, hot and dry, temperate, cold and composite. Chennai has been chosen for hot and humid conditions, Jodhpur for hot and dry condition, Bangalore for temperate condition, Leh for cold condition and Gurugram for composite climatic conditions. In all these climatic conditions, we have analysed the sample data using PVSOL simulation software.

Performance ratio (PR) is the major factor to calculate the system performance. From IEC 61724, performance ratio is defined as the ratio of energy Yield (E_y) to reference yield (E_r). After simulating the data we found the PR value of 0.86 for Leh (L), 0.83 for Gurugram (G), 0.82 for Bangalore (B), 0.82 for Jodhpur (J) and 0.82 % for Chennai (C).

From these PR values, we may say that the HIT module works comparatively better in cold climatic condition. The HIT modules employed in this study have a rating of 210 Wp. Table 4.3 lists the PR values calculated in different climatic conditions prevailing in India along with statistical analysis of the PR data.

Table 4.3 The PR values for HIT modules studied in different climatic zones

	PR Gurugram	PR Bangalore	PR Chennai	PR Jodhpur	PR Leh
Mean	0.829	0.825	0.820	0.821	0.865
Median	0.825	0.824	0.820	0.816	0.858
Mode	.798	.813	.806	.7930	.825
Std. Deviation	0.025	0.007	0.009	0.021	0.034
Minimum	0.799	0.814	0.806	0.793	0.825
Maximum	0.870	0.836	0.832	0.854	0.914

HIT module, each with a wattage of around 210 Wp, was used to install 1.68 kWp power plant at each location mentioned above. The tilt angles for the location for Gurugram, Bangalore, Chennai, Jodhpur and Leh respectively are 28°, 13°, 13°,26°, and 34°. The details are given in Table 4.4

Table 4.4 Tilt angle from different climatic zones

Location	Gurugram	Bangalore	Chennai	Jodhpur	Leh
Tilt angle	28°	13°	13°	26°	34°

The module electrical parameters are open circuit voltage 51.6 V, short circuit current 5.47 A, maximum voltage 42 V , maximum current 5 A and module wattage is 210 Wp. The details are given in Table 4.5

Table 4.5 HIT module electrical parameters

MPP Voltage	MPP Current	Open Circuit Voltage	Short-Circuit Current	Power Rating	Plant Capacity
42 V	5 A	51.6 V	5.47 A	210 W	1.68 kWp

HIT module mechanical data also consider for designing the power plant. The module width is around 862 mm, height 1630 mm, depth 35 mm and weight 26 kg. The details are given in table 4.6.

Table 4.6 HIT module mechanical data

Width	Height	Depth	Weight
862 mm	1630 mm	35 mm	26 kg

The performance ratio of HIT technologies modules in different climatic zones has been estimated on monthly basis (please see table 4-7). From the table 4-7, we see that the performance ratio for Gurugram location varies from 0.79 to 0.87, for Bangalore location PR varies from 0.81 to 0.83, for Chennai location PR varies from 0.80 to 0.83, for Jodhpur location PR varies from 0.79 to 0.85 and for Leh location PR varies from 0.82 to 0.91. The highest variation in the PR values may be seen at Gurugram and Leh, which has composite and cold climates, respectively.

Table 4.7 Monthly variation in PR values for different climatic zones

Month	PR Gurugram	PR Bangalore	PR Chennai	PR Jodhpur	PR Leh
Jan	0.870153	0.828569	0.831912	0.854243	0.914006
Feb	0.854276	0.822576	0.829998	0.843733	0.899365
Mar	0.833754	0.817884	0.822322	0.82223	0.873476
Apr	0.810452	0.813778	0.815064	0.806946	0.861525
May	0.798802	0.816256	0.806339	0.793095	0.847997
Jun	0.802925	0.821482	0.809549	0.795815	0.838192
Jul	0.808515	0.820188	0.809071	0.805327	0.825116
Aug	0.810741	0.825161	0.814313	0.812026	0.82772
Sep	0.82124	0.832716	0.817196	0.814422	0.827666
Oct	0.829136	0.830329	0.821879	0.81662	0.853632
Nov	0.84867	0.83481	0.82947	0.836728	0.89444
Dec	0.863032	0.836134	0.8315	0.849471	0.913746

Figure 4.9 shows the monthly variation of PR in different climatic zones. The performance ratio value is also dependent on temperature variation. If the condition is cold, such as in Leh region, the performance ratio is the best. The same may be verified from the table 4.7. In Figure 4.10, the PR data shows the monthly variation in PR values, and the bar graph represents the value of the PR for each month for each of the location PR-G for Gurugram, PR-B Bangalore, PR- C Chennai, PR – J Jodhpur and PR-L for Leh.

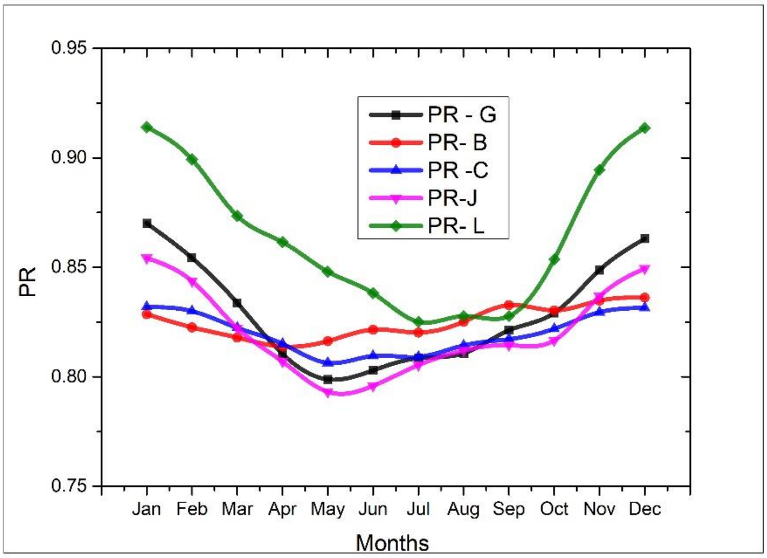


Figure 4.9 - Monthly PR value for different climatic zones

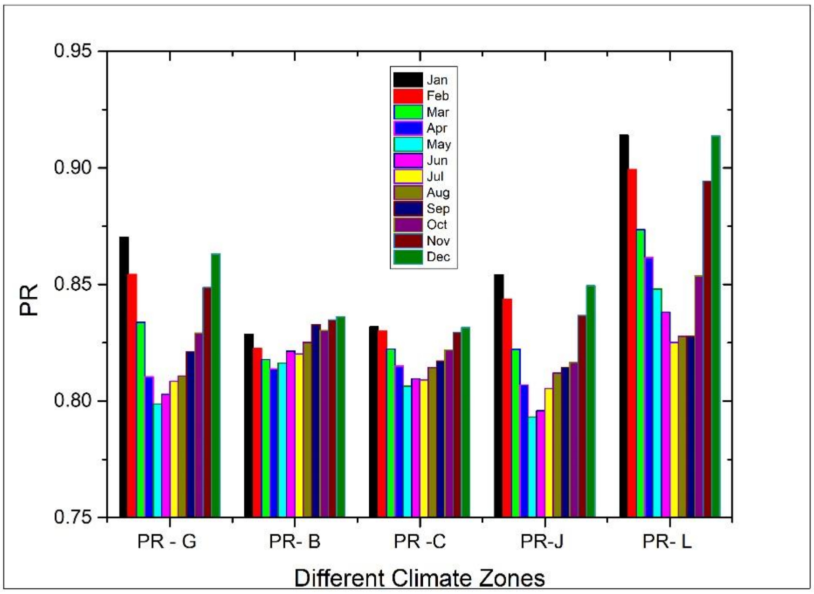


Figure 4.10 Bar Graph for monthly PR values in HIT modules

In statistics, a frequency distribution is a graph or data set that displays the likelihood of each possible outcome of a repeated event that has been observed numerous times. When assigning probabilities to huge data sets and describing them, frequency distributions are very helpful. The frequency distribution for the PR in different climatic location is shown in figure 4.11: (a) represents the PR for Gurgaon, (b) for Bangalore, (c) for Chennai, (d) for Leh and (e) for Jodhpur. In fig 4.11 (a), which represents the frequency distribution of PR in Gurgaon region, most of the time PR value lies between 0.80 to 0.82; the mean and standard deviation is approx. 0.82 and 0.024. Fig 4-11 (b) shows the frequency distribution of PR in Bangalore region: the maximum value of PR lies between 0.80 to 0.83; the mean and standard deviation is 0.82 and 0.007. In fig 4-11 (c), the frequency distribution of PR in Chennai regions is represented: most of the time maximum value of PR value lies between 0.80 to 0.81; the mean and standard deviation is 0.82 and 0.009. Fig 4-11 (d) shows the frequency distribution of PR in Leh region; maximum value of PR value lies between 0.82 to 0.84; the mean and standard deviation is 0.864 and 0.033. In fig 4-11 (e), the frequency distribution of PR in Jodhpur region has been represented: most of the time PR value lies in the range 0.80 - 0.82; the mean and standard deviation is 0.820 and 0.020.

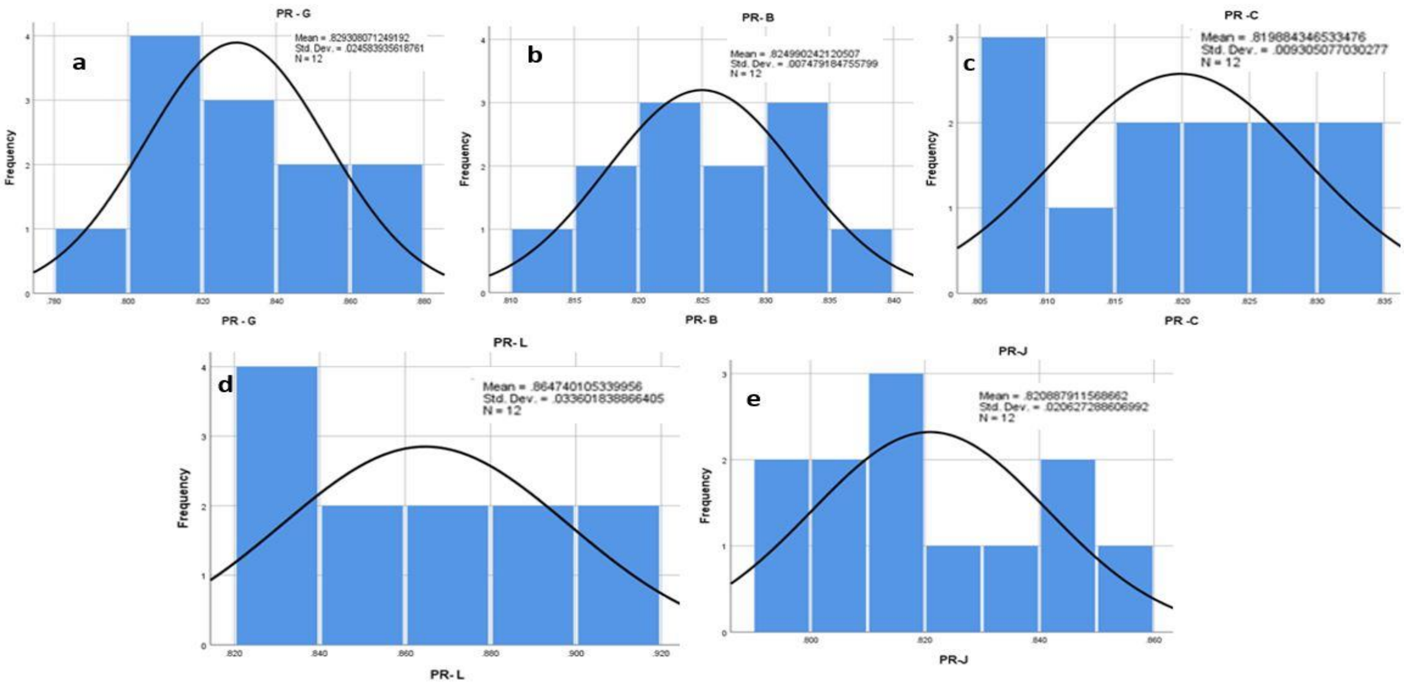


Figure 4.11 Frequency distribution in different climatic condition

4.3 Performance Analysis of Different PV module Technologies for different climatic conditions of India

Six types of module technologies were used in this study. These are multi-crystalline silicon, amorphous-Si thin-film module, HIT module, Cadmium Telluride (CdTe) thin-film module, Copper Indium Gallium Selenide (CIGS) thin-film module, and Integrated Back contact technologies (IBC) module. All the modules were installed in composite climatic conditions. Similar technology modules and module references have also been used in various other climatic zones in India as well. Tables 4-8, 4-9 and 4-10 contain the details (electrical parameters, physical dimensions, weight, manufacturer, etc.) of various modules used in this study. Other details like voltage temperature coefficient, current temperature coefficient, power temperature coefficient and maximum system voltage of all the module technologies used in this study have been given in table 4.10 . We see that a-Si has the smallest power temperature coefficient among various technologies panels used in this study.

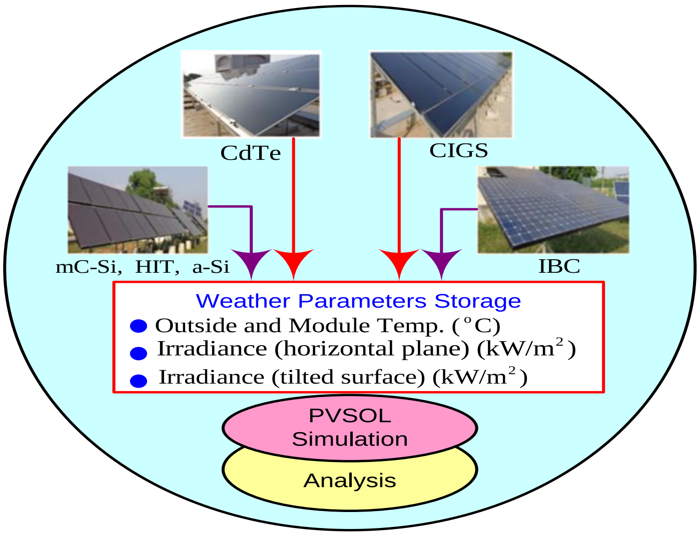


Figure 4.12 Different Outdoor PV module technology

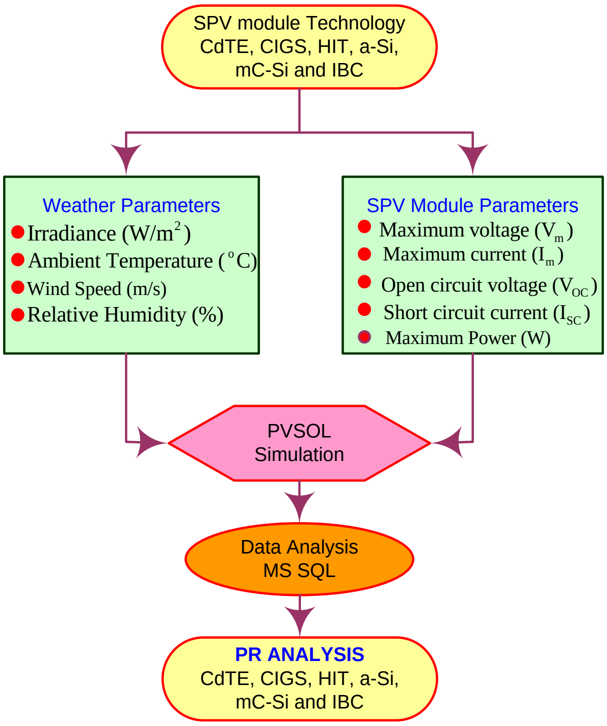


Figure 4.13 The schematic showing the investigation of the performance of various technology modules

Table 4.8 Electrical parameters of different technologies solar PV modules

Sr. No	Technologies	Company	MPP Voltage	MPP Current	Open Circuit Voltage	Short-Circuit Current	Power Rating	Plant Capacity
1	CdTe	First Solar	48.5 V	1.65 A	60.8 V	1.88 A	80 W	3.2 kWp
2	CIGS	Stion	42.7 V	2.81 A	55.2 V	3.32 A	120 W	1.2 kWp
3	HIT	Panasonic	42 V	5 A	51.6 V	5.47 A	210 W	1.68 kWp
4	a-Si	Kaneka	67 V	1.12 A	91.8 V	1.4 A	75 W	1.2 kWp
5	mC-Si	Sharp	23.2 V	7.55 A	39.8 V	8.29 A	175 W	1.58 kWp
6	IBC	SunPower	54.7 V	5.98 A	64.9 V	6.46 A	327 W	1.64 kWp

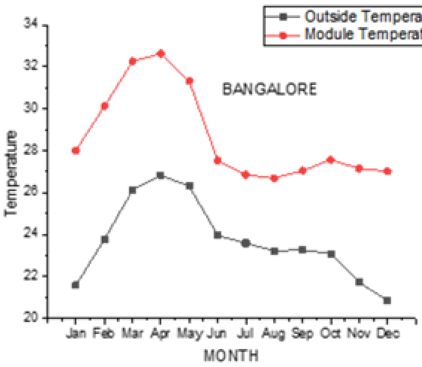
Table 4.9 Physical dimensions and weight of various module technologies

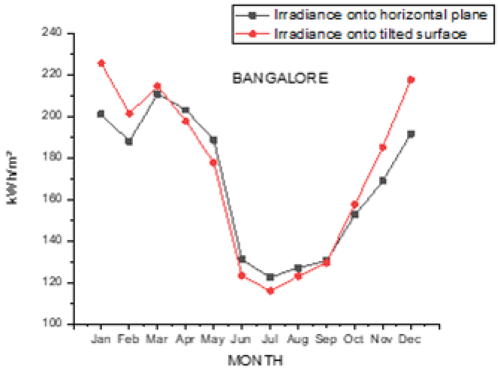
Sr. No	Technologies	Company	Width	Height	Depth	Weight
1	CdTe	First Solar	600 mm	1200 mm	7 mm	12 kg
2	CIGS	Stion	655 mm	1675 mm	35 mm	16.8 kg
3	HIT	Panasonic	862 mm	1630 mm	35 mm	26 kg
4	a-Si	Kaneka	1008 mm	1210 mm	40 mm	18.3 kg
5	mC-Si	Sharp	994 mm	1318 mm	46 mm	15.5 kg
6	IBC	SunPower	1046 mm	1559 mm	46 mm	18.6 kg

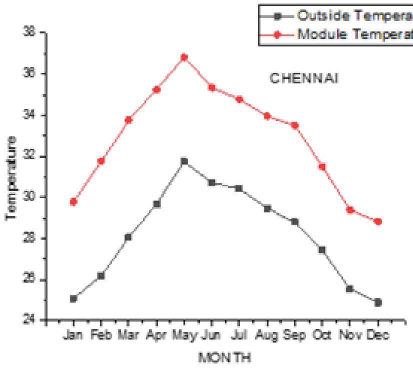
Table 4.10 Other electrical parameters of various PV module technologies

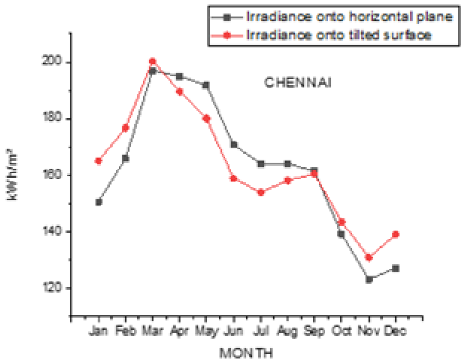
Sr. No	Technologies	Company	Voltage temp Coefficient	Current temp Coefficient	Power temp Coefficient	Maximum System Voltage
1	CdTe	First Solar	-152.5 mV/K	0.79 mA/K	-0.25 %/K	1000 V
2	CIGS	Stion	-182.16 mV/K	0.03 mA/K	-0.39 %/K	1000 V
3	HIT	Panasonic	-129 mV/K	1.64 mA/K	-0.3 %/K	1000 V
4	a-Si	Kaneka	-279.99 mV/K	1.05 mA/K	-0.14 %/K	600 V
5	mC-Si	Sharp	-97.55 mV/K	1.71 mA/K	-0.46 %/K	1000 V
6	IBC	SunPower	-176.6 mV/K	3.5 mA/K	-0.38 %/K	1000 V

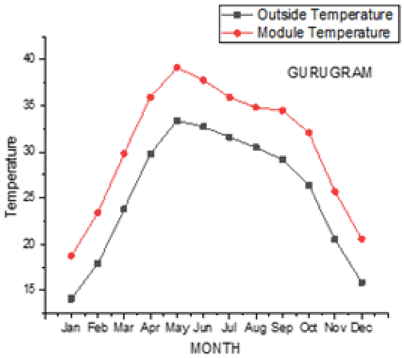
Figure 4.14 gives a graphical description of weather parameters (ambient temperature and irradiance) at representative locations in different climatic zones. This data is the input to the PVSOL software, in addition to the various modules characteristics, which gives us the performance estimation of different PV module technologies in various climatic zones.

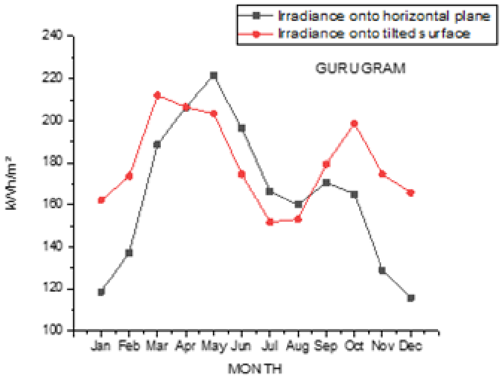

Outside Temperature
Module Temperature
BANGALORE
Temperature
MONTH

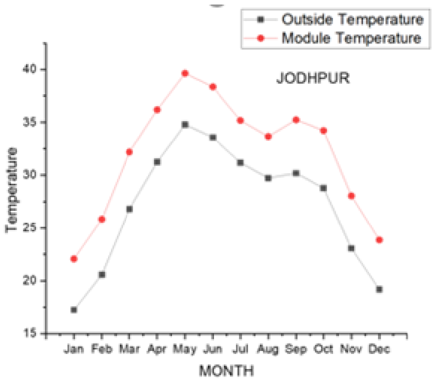

Irradiance onto horizontal plane
Irradiance onto tilted surface
BANGALORE
MONTH

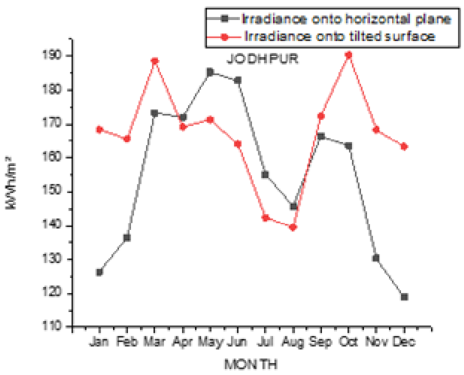

Outside Temperature
Module Temperature
CHENNAI
Temperature
MONTH

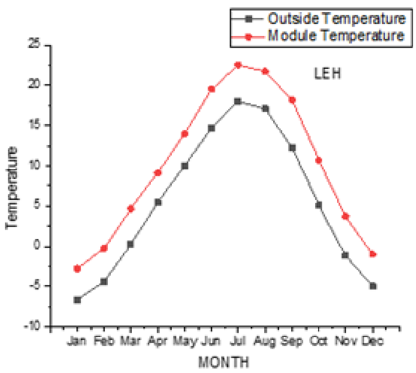

Irradiance onto horizontal plane
Irradiance onto tilted surface
CHENNAI
MONTH


Outside Temperature
Module Temperature
GURUGRAM
Temperature
MONTH


Irradiance onto horizontal plane
Irradiance onto tilted surface
GURUGRAM
MONTH


Outside Temperature
Module Temperature
JODHPUR
Temperature
MONTH


Irradiance onto horizontal plane
Irradiance onto tilted surface
JODHPUR
MONTH


Outside Temperature
Module Temperature
LEH
Temperature
MONTH

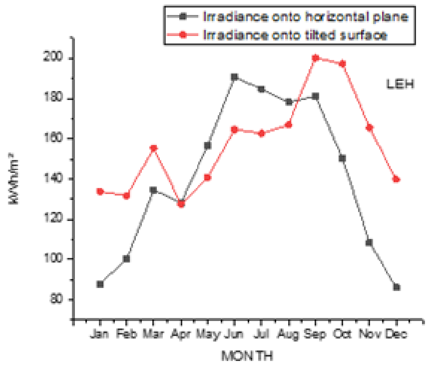

Irradiance onto horizontal plane
Irradiance onto tilted surface
LEH
MONTH

Figure 4.14 Weather parameters (ambient temperature and irradiance) at different spots in various climatic zones. This data is used in PVSOL to estimate the performance of various PV technologies modules.

The performance of all the PV technologies modules in different climatic conditions has been displayed in Figure 4.15

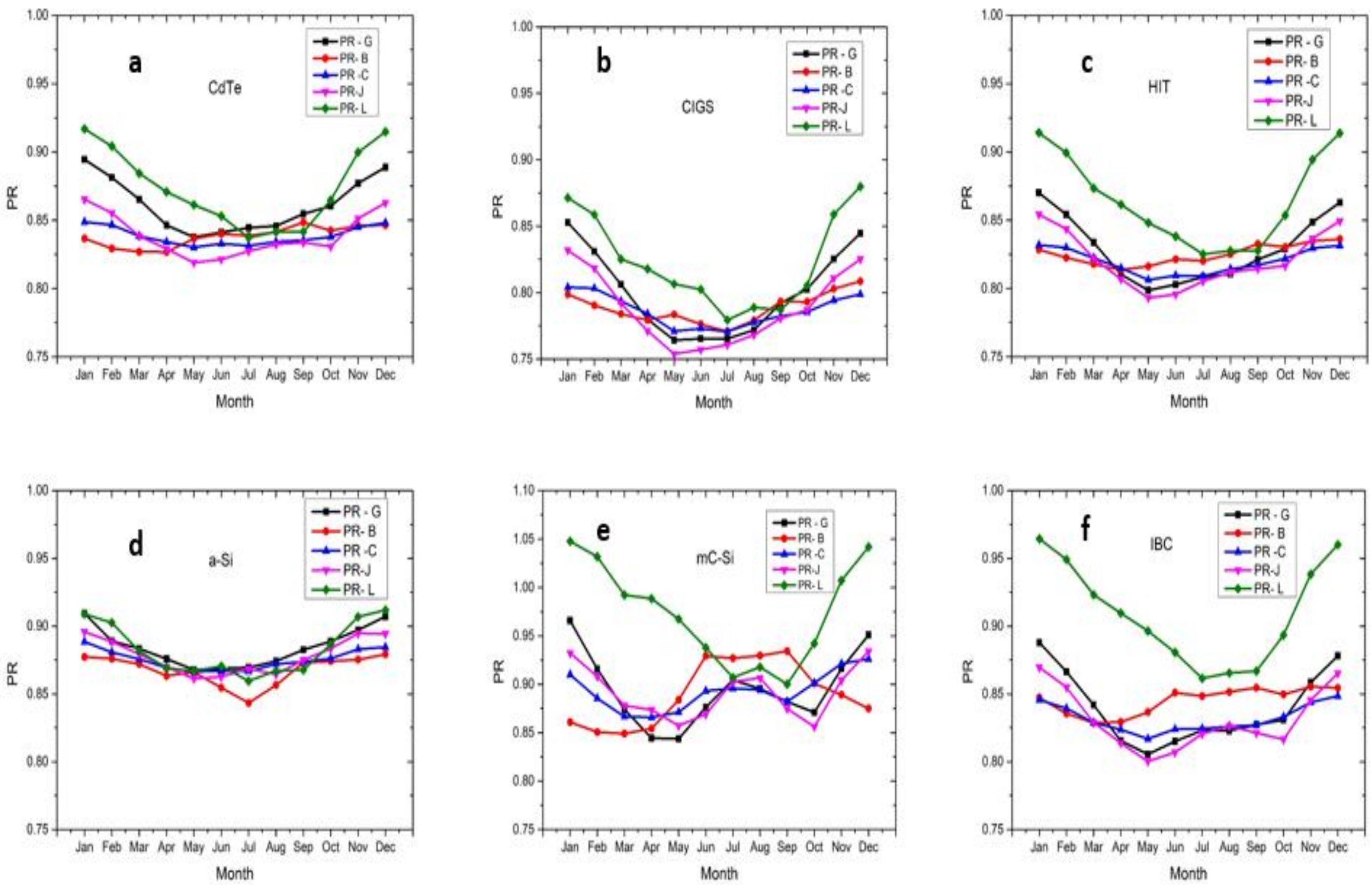


Figure 4.15 Monthly performance ratio (PR) of various PV technologies modules under different climatic conditions prevailing in India. PR-G, PR-B, PR-C, PR-J, and PR-L represent the performance ratio of various modules in Gurugram (composite), Bangalore (moderate), Chennai (warm & humid), Jaipur (hot & dry) and Leh (cold).

All the technologies modules seem to perform best in the cold regions (e.g. in Leh). Especially during the winter months (October to January), almost all the technologies modules show a rise in the performance in all the climatic zones considered in the study. In the case of mc-Si, however, the performance is observed to decrease during winter and increase during summer (which later becomes constant), when it is employed in moderate conditions (Bangalore) (Figure 4-15). In a-Si PV modules, the performance is more or less similar in all the climatic conditions as compared to other PV technologies modules. This might be due to the low temperature coefficient of a-Si module of special mention is the performance of mc-Si and IBC technologies modules throughout the year in various climatic zones.

The suitability of different technologies modules in various climatic zones has also been investigated. Figure 4.16. Shows the monthly performance of different technologies modules in various climatic zones.

The performance ratio is affected by irradiation, the optimal tilt angle, air temperature, design parameters, module quality, and so on. Standard Test Conditions (STC) are generally used to rate module performance: irradiance of 1000 W/m^2, solar spectrum of AM 1.5, and module temperature of 25°C.

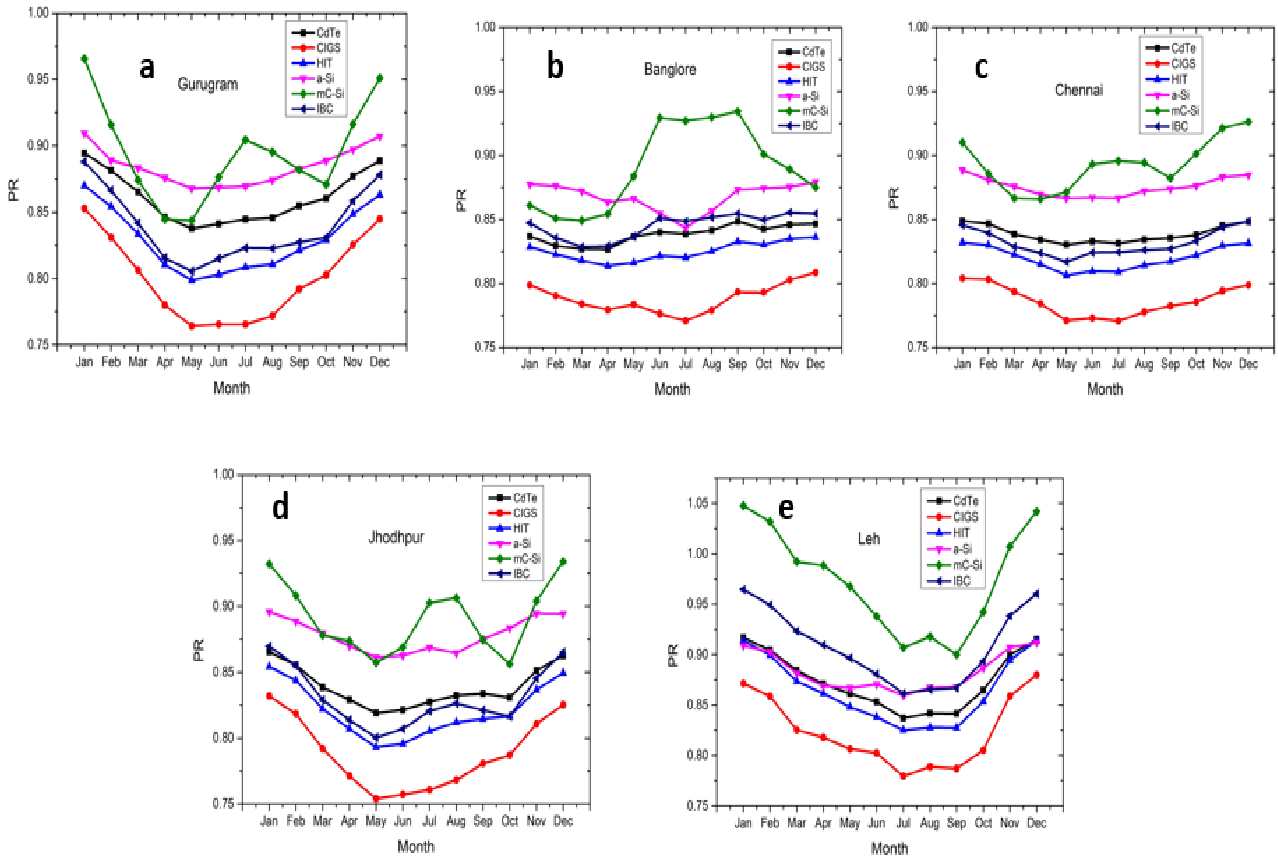


Figure 4.16 Monthly performance of various technologies modules in different climatic zones: (a) Gurugram (composite), (b) Bangalore (moderate), (c) Chennai (warm & humid), (d) Jodhpur (hot & dry) and (e) Leh (cold).

From Figure 4.16 (a), we see that in composite climate (Gurugram), mc-Si technology performs better, especially during winter, followed by the performance of a-Si. Performance of a-Si seems almost the same throughout the year. CIGS technologies has the lowest performance in composite climate.

In moderate climate (e.g. Bangalore) (Figure 4.16 (b)), the performance of almost all the technologies modules shows less variation throughout the year, except in the case of mc-Si: performance of mc-Si modules increases during the summer, and this increase is found to be steep in April, May and June, after which the performance remains constant until September. This peculiar behavior might be due to module quality. In this zone, the performance of CIGS is the lowest.

In warm & humid regions (e.g. Chennai) (Figure 4.16 (c)), the performance of mc-Si and a-Si technologies seem almost similar. Although the performance of mc-Si is slightly better as compared to a-Si during winter, the variation in the performance of mc-Si throughout the year is quite substantial as compared to a-Si. Except for mc-Si, the performance of all other technologies modules is almost similar throughout the year. CIGS technologies modules have the lowest performance in this region as well.

In the hot & dry region (e.g. Jodhpur) (Figure 4.16 (d)), the average performance of mc-Si and a-Si seems to be almost the same throughout the year; during winter, however, the performance of mc-Si is a bit higher than a-Si. The performance of a-Si modules has the least variation as compared to other technologies modules. CIGS modules have the least performance in this region as well.

In cold regions (e.g. Leh) (Figure 4.16 (e)), mc-Si modules show the best performance, especially during winter, although the modules' performance varies significantly (approx. by 12%) throughout the year. The performance of a-Si modules is, surprisingly, not on expected grounds, as its performance is lower than IBC modules. The performance of CIGS modules is lowest in this region as well

From the above discussion, it seems that the reliability of a-Si is higher than other technology PV modules in all climatic zones except in cold zone, because of very little variability in performance throughout the year. The performance of mc-Si modules is erratic: during winter, it shows very good performance, which decreases significantly during summer. Therefore, in regions where the temperature is very low throughout the year, mc-Si may be used for renewable energy harvesting.

In order to understand the reliability of the performance of various technologies modules, average (arithmetic mean of monthly PR) and variability (standard deviation in PR) in their performance has been plotted w.r.t the PV technologies in different climatic zones (Figure 4.17). The technologies having higher average performance and less variability throughout the year might be considered as a reliable technologies in that particular climatic zone.

From Figure 4.17 , we see that in almost all the climatic zones, a-Si technologies provides stable performance with very little variation in the performance throughout the year. In particular, the performance of a-Si is very impressive in different climatic conditions such as composite, warm & humid and hot & dry. This is clear from table 4-10, in which the power temperature coefficient of all the technologies panels is displayed. The a-Si technologies panels have a very small temperature coefficient, which enables these panels to limit the loss in power due to an increase in module/ambient temperature. The average performance of mc-Si technologies is highest in all the climatic zones, but variation in its performance is also substantial: especially, as the module/ambient temperature increases, the performance of these panels decreases significantly (Figure 4.17). This may also be explained by the very high power temperature coefficient of mc-Si modules. The worst performing technologies is CIGS in all the climatic conditions.

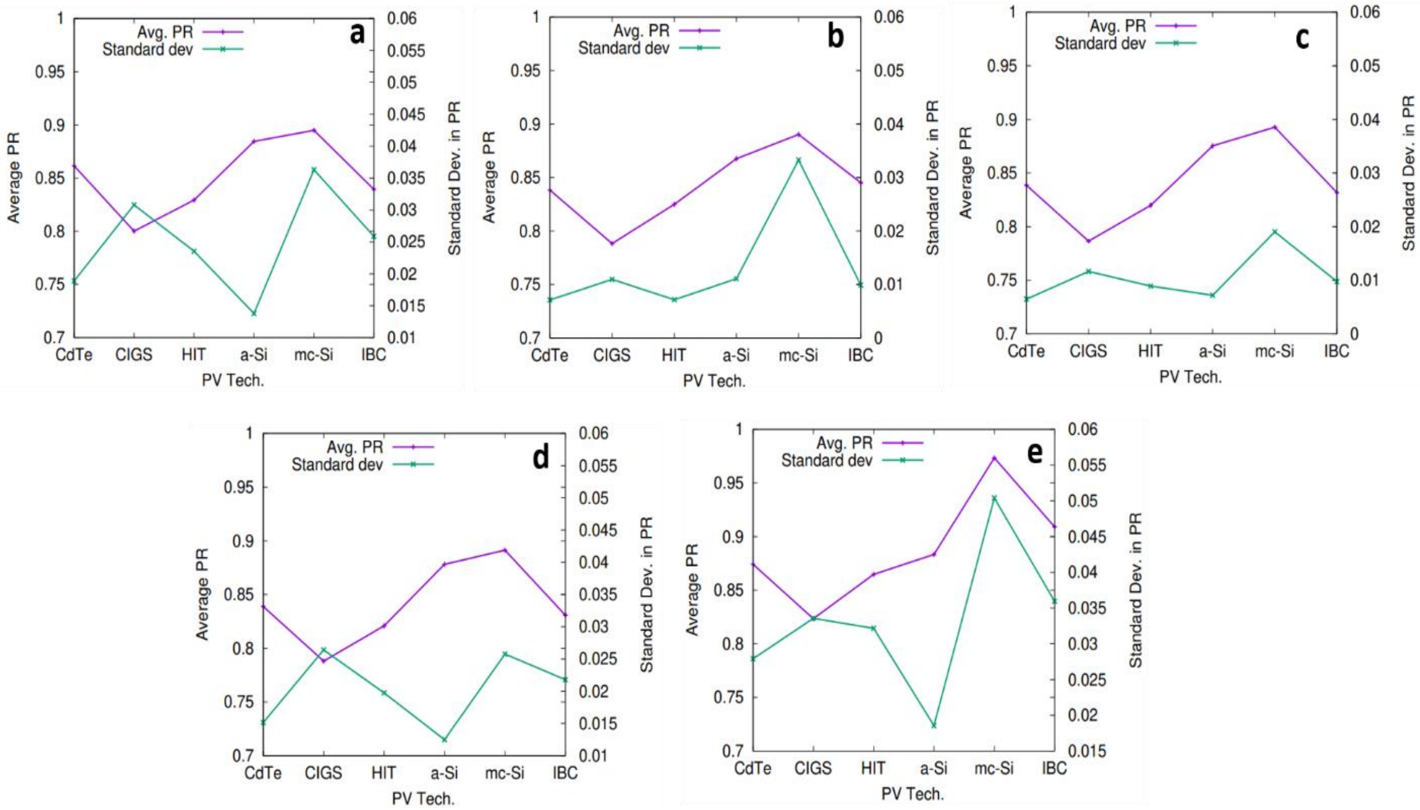


Figure 4.17 Average and variability in performance of various technologies in different climatic zones: (a) Gurugram (composite); (b) Bangalore (moderate); (c) Chennai (warm & humid); (d) Jaipur (hot & dry) and (c) Leh (cold)

The above results and subsequent analysis of the performance of various technologies have been done based on the calculations of PVSOL software, as has been detailed above. The credibility of the PVSOL simulations has been validated using real performance estimation data in composite climate at Gurugram. All the PV technologies modules have been installed physically at the NISE campus (Gurugram), and real-time data from all the technologies modules have been captured to calculate the performance ratio. Figure **4.18** represents a histogram of the performance ratios calculated from PVSOL and using real-time data from all the PV technologies panels installed at the NISE campus.

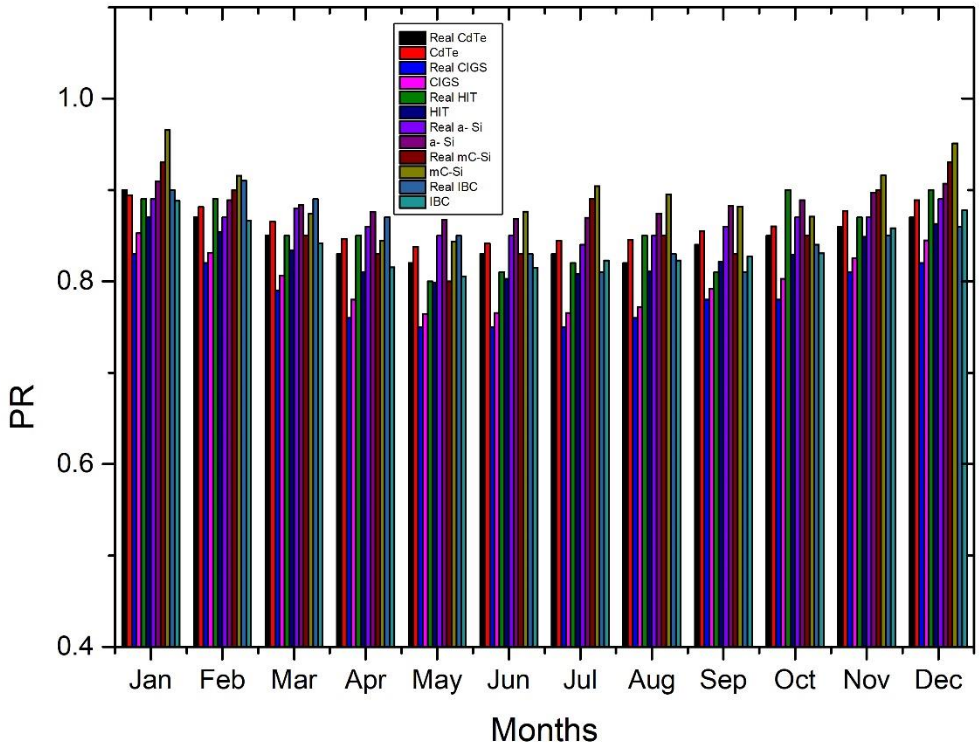


Figure 4.18 Monthly comparison between the real and calculated (from software) performance ratios of different module technologies in composite climate (Gurugram) conditions.

The performance ratio is the primary parameter that needs to be determined in accordance with IEC 61724 standards in order to examine the performance of the SPV plant. Other than irradiance, the PR equation does not account for other weather-related variables. However, it is crucial to take into account how temperature affects the effectiveness of PV modules. The output power of PV modules varies with temperature. The parameter that takes into account how temperature affects module output power is called the temperature coefficient of the power. The value of the DC electrical power output, when 1000 W/m^2 of solar insolation incident on the full solar PV module active area at 25 °C, with an air mass ratio of 1.5, is simply the module's rated output power. Winter is the time when the system operates at its best. This is mostly caused by the intermittent cooling that occurs at the module surface as a result of the cold winds and lower T_{amb} values, which prevents the surface of the module from reaching high Temperatures as in summers. As a result, the values of T_{mod} during this time are generally lower than during other seasons. The winter season has the highest PR value compared to the other seasons. This suggests that T_{mod} and T_{amb} have a significant impact on PR.

The real and calculated performance ratios of various module technologies have been analyzed further by calculating the percentage change in PR values:

$$\%\text{Change in } PR = \frac{PR_{\mathrm{REAL}} - PR_{\mathrm{CAL}}}{PR_{\mathrm{REAL}}} \times 100$$

Where PR_{REAL} is the performance ratio calculated using real-time data obtained from the module technologies installed at NISE campus, Gurugram, and PR_{CAL} is the performance ratio calculated using PVSOL software. Both the performance ratios (PR_{REAL} and PR_{CAL}) and the percentage change in both the values have been plotted along with the mean percentage change in Figure 4.19 .

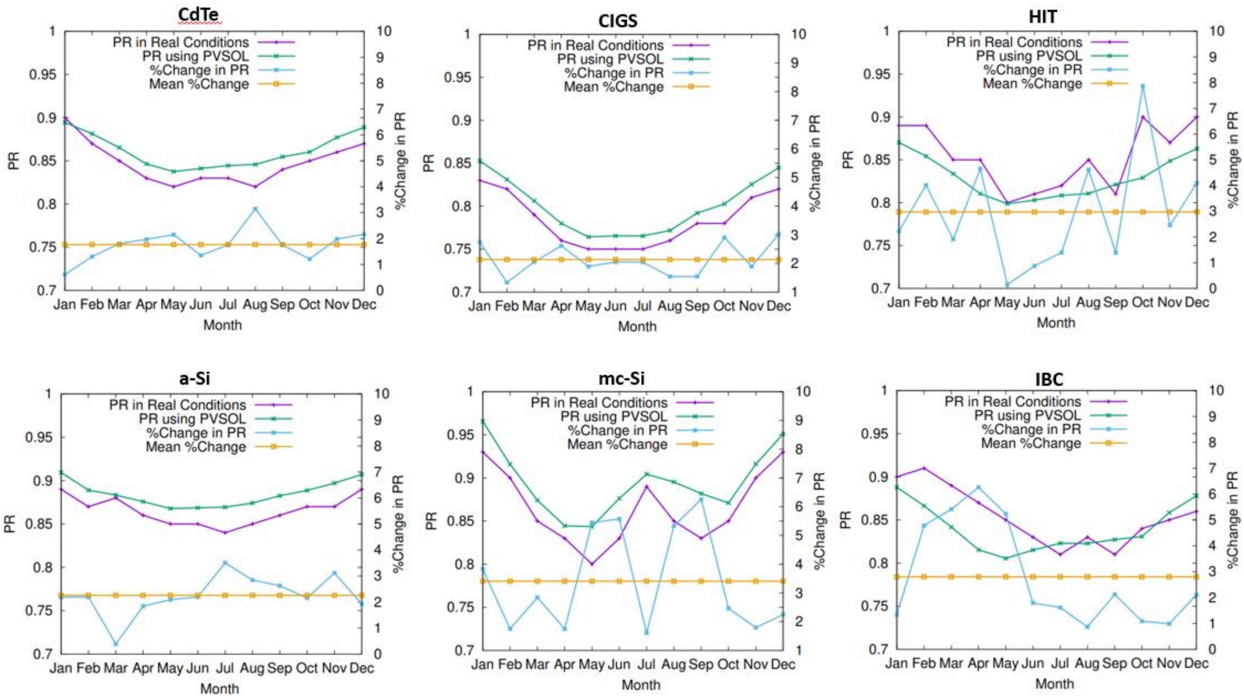


Figure 4.19 The performance ratios of various module technologies estimated using real-time conditions and that using PVSOL software (in composite climate) have been displayed here. In addition, the percentage change in both the performance ratios along with the mean percentage change in the performance ratios has been plotted.

From Figure 4.19, we see that the monthly trend of the performance ratios in all the module technologies, whether calculated using PVSOL or using real-time data, is almost the same. In the case of CdTe, CIGS and a-Si module technologies, the performance predicted using PVSOL is very close to that obtained using the real-time data. The mean percentage change in these module technologies is approx. 2%, which is encouraging. Maximum percentage change in the performance ratios is observed in mc-Si (3.4%), followed by HIT (2.97%) and IBC (2.8%).

4.3.1 Relative PR of different technology modules with reference to mc-Si

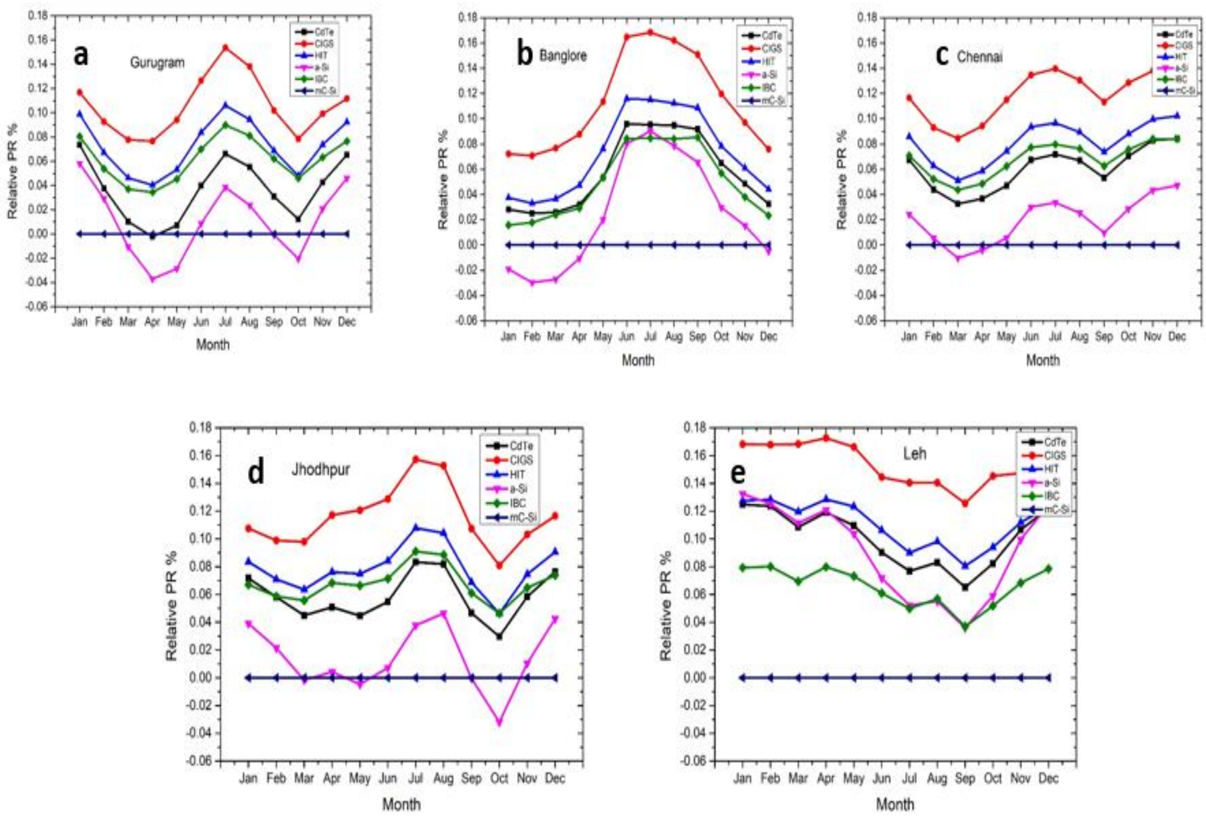


Figure 4.20 Relative percentage change in PR of different technology modules with reference to mc-Si for different climatic conditions

Since mc-Si technology is standard technology and very well understood, we have calculated the relative change in PR of all technology modules with reference to the PR of mc-Si technology using the following expression:

$$\text{Relative PR}(\%) = \frac{\text{PR}_{\text{mc-Si}} - \text{PR}_{\text{j}}}{\text{PR}_{\text{mc-Si}}} \times 100$$

where j = CdTe, CIGS, HIT, IBC and a-Si

The relative percentage change in the PR w.r.t. the mc-Si has been plotted for different climatic conditions in figure 4-20. A positive value of relative PR means that performance of that particular technology is less vis-à-vis the performance of mc-Si technology, and vice versa for the negative value. We see during certain months in the year, a-Si technology has outperformed mc-Si in almost all climatic conditions, except in Leh. In Leh, mc-Si seems to be the best technology throughout the year. Performance of CIGS technology is found to be the worst amongst all the technology modules considered for study in the current research.

4.3.2 Durability and cost effectiveness of solar module

Solar module's productive lifetime is around 25-30 years. After this lifetime, the module still produces the power, but it will be minimum as per the manufacturer rated capacity. Solar modules are not damaged by wind and snow load; external effects are responsible for the damage of solar module. All solar module manufacturers give the manufacturing defects and performance warranty of all the solar modules. If the modules are properly operated and maintained, the lifetime of the module as well its performance will be optimal.

Module performance is also measured using Return of Investment (ROI) or payback period of installation of solar power plant. In our study, Return of Investment (ROI) of different types of solar modules is found to depend on the module technology and location. PVSOL software has been used to analyse the financial aspects of different types of modules employed in the present investigation. The details are given in tables 4.11, 4.12, 4.13, 4.14, 4.15, 4.16. These tables provide a financial study of several climate zones and provide information on cash flow, return on investment, electricity cost and savings, and ruminations. From these tables, the decision regarding choosing and investing in various technologies may be made.

Table 4.11 CdTe Financial analysis

CdTe	Gurugram	Bangalore	Jodhpur	Chennai	Leh
Analysis of the Financial Situation					
Information about the system					
Grid Feed-in in the first year (including module degradation) kWh/Year	5179	5565	5652	5084	5455
PV Generator Output kWp	3.2	3.2	3.2	3.2	3.2
Start of Operation of the System	7-12-2021	7-12-2021	7-12-2021	7-12-2021	7-12-2021
Assessment Period Years	20	20	20	20	20
Economic Parameters					
Return on Assets %	19.47	20.96	21.36	19.09	20.63
Accrued Cash Flow (Cash Balance) ₹	358854.79	394614.56	403116.14	349983.82	385024.81
Return of investment Years	5.2	4.8	4.7	5.2	4.9
Electricity Production Costs ₹/kWh	1.31	1.22	1.2	1.34	1.24
Payment Overview					
Specific Investment Costs ₹/kWp	40000	40000	40000	40000	40000
Investment Costs ₹	128000	128000	128000	128000	128000
Savings and remuneration					
Total Utility Payment in the First Year/Year₹/Year	25896.18	27827.29	28257.89	25418.39	27274.6
Validity	2021-2046	2021-2046	2021-2046	2021-2046	2021-2046
Specific feed-in / export Remuneration ₹/kWh	5	5	5	5	5
Feed-in / Export Tariff ₹/Year	25896.18	27827.29	28257.89	25418.39	27274.6

Table 4.12 CIGS Financial analysis

CIGS	Gurugram	Bangalore	Jodhpur	Chennai	Leh
Analysis of the Financial Situation					
Information about the system					
Grid Feed-in in the first year (including module degradation) kWh/Year	1831	1958	1988	1783	1963
PV Generator Output kWp	1.2	1.2	1.2	1.2	1.2
Start of Operation of the System	7-12-2021	7-12-2021	7-12-2021	7-12-2021	7-12-2021
Assessment Period Years	20	20	20	20	20
Economic Parameters					
Return on Assets %	18.24	19.55	19.93	17.73	19.72
Accrued Cash Flow (Cash Balance) ₹	124071.84	135823.71	138806.3	119660.93	136589
Return of investment Years	5.5	5.1	5	5.6	5.1
Electricity Production Costs ₹/kWh	1.39	1.3	1.28	1.43	1.3
Payment Overview					
Specific Investment Costs ₹/kWp	40000	40000	40000	40000	40000
Investment Costs ₹	48000	48000	48000	48000	48000
Savings and remuneration					
Total Utility Payment in the First Year/Year₹/Year	9154.49	9789.68	9940.98	8917.3	9815.37
Validity	2021-2046	2021-2046	2021-2046	2021-2046	2021-2046
Specific feed-in / export Remuneration ₹/kWh	5	5	5	5	5
Feed-in / Export Tariff ₹/Year	9154.49	9789.68	9940.98	8917.3	9815.37

Table 4.13 HIT financial analysis

HIT	Gurugram	Bangalore	Jodhpur	Chennai	Leh
Analysis of the Financial Situation					
Information about the system					
Grid Feed-in in the first year (including module degradation) kWh/Year	2607	2787	2835	2547	2759
PV Generator Output kWp	1.68	1.68	1.68	1.68	1.68
Start of Operation of the System	7-12-2021	7-12-2021	7-12-2021	7-12-2021	7-12-2021
Assessment Period Years	20	20	20	20	20
Economic Parameters					
Return on Assets %	15.48	16.66	17.03	15.08	16.55
Accrued Cash Flow (Cash Balance) ₹	166026.94	182703.63	187378.32	160471.32	180432.09
Return of investment Years	6.3	5.9	5.8	6.5	6
Electricity Production Costs ₹/kWh	1.61	1.5	1.48	1.64	1.52
Payment Overview					
Specific Investment Costs ₹/kWp	47000	47000	47000	47000	47000
Investment Costs ₹	78960	78960	78960	78960	78960
Savings and remuneration					
Total Utility Payment in the First Year/Year₹/Year	13033.19	13934.68	14172.77	12734.36	13792.62
Validity	2021-2046	2021-2046	2021-2046	2021-2046	2021-2046
Specific feed-in / export Remuneration ₹/kWh	5	5	5	5	5
Feed-in / Export Tariff ₹/Year	13033.19	13934.68	14172.77	12734.36	13792.62

Table 4.14 a-Si Financial analysis

a-Si	Gurugram	Bangalore	Jodhpur	Chennai	Leh
Analysis of the Financial Situation					
Information about the system					
Grid Feed-in in the first year (including module degradation) kWh/Year	1948	2052	2137	1910	1909
PV Generator Output kWp	1.2	1.2	1.2	1.2	1.2
Start of Operation of the System	7-12-2021	7-12-2021	7-12-2021	7-12-2021	7-12-2021
Assessment Period Years	20	20	20	20	20
Economic Parameters					
Return on Assets %	19.52	20.55	21.53	19.12	19.12
Accrued Cash Flow (Cash Balance) ₹	135118.33	144604.84	152761.61	131582.06	131471.32
Return of investment Years	5.1	4.9	4.7	5.2	5.2
Electricity Production Costs ₹/kWh	1.31	1.24	1.19	1.33	1.33
Payment Overview					
Specific Investment Costs ₹/kWp	40000	40000	40000	40000	40000
Investment Costs ₹	48000	48000	48000	48000	48000
Savings and remuneration					
Total Utility Payment in the First Year/Year₹/Year	9742.23	10258.79	10684.01	9551.98	9543.43
Validity	2021-2046	2021-2046	2021-2046	2021-2046	2021-2046
Specific feed-in / export Remuneration ₹/kWh	5	5	5	5	5
Feed-in / Export Tariff ₹/Year	9742.23	10258.79	10684.01	9551.98	9543.43

Table 4.15 mC-Si Financial analysis

mc-Si	Gurugram	Bangalore	Jodhpur	Chennai	Leh
Analysis of the Financial Situation					
Information about the system					
Grid Feed-in in the first year (including module degradation) kWh/Year	2699	2818	2865	2626	3010
PV Generator Output kWp	1.6	1.6	1.6	1.6	1.6
Start of Operation of the System	7-12-2021	7-12-2021	7-12-2021	7-12-2021	7-12-2021
Assessment Period Years	20	20	20	20	20
Economic Parameters					
Return on Assets %	21.83	22.77	23.23	21.23	24.53
Accrued Cash Flow (Cash Balance) ₹	193762.53	204688.97	209336.43	186923.76	223143.01
Return of investment Years	4.6	4.4	4.4	4.7	4.1
Electricity Production Costs ₹/kWh	1.18	1.13	1.11	1.21	1.05
Payment Overview					
Specific Investment Costs ₹/kWp	38000	38000	38000	38000	38000
Investment Costs ₹	59850	59850	59850	59850	59850
Savings and remuneration					
Total Utility Payment in the First Year/Year₹/Year	13495.3	14088.64	14327.3	13127.7	15050.4
Validity	2021-2046	2021-2046	2021-2046	2021-2046	2021-2046
Specific feed-in / export Remuneration ₹/kWh	5	5	5	5	5
Feed-in / Export Tariff ₹/Year	13495.3	14088.64	14327.3	13127.7	15050.4

Table 4.16 IBC Financial analysis

IBC	Gurugram	Bangalore	Jodhpur	Chennai	Leh
Analysis of the Financial Situation					
Information about the system					
Grid Feed-in in the first year (including module degradation) kWh/Year	2617	2819	2845	2568	2845
PV Generator Output kWp	1.6	1.6	1.6	1.6	1.6
Start of Operation of the System	7-12-2021	7-12-2021	7-12-2021	7-12-2021	7-12-2021
Assessment Period Years	20	20	20	20	20
Economic Parameters					
Return on Assets %	15.66	16.99	17.21	15.33	17.26
Accrued Cash Flow (Cash Balance) ₹	167437.7	186123.74	188771.64	162907.73	189048.59
Return of investment Years	6.3	5.8	5.8	6.4	5.8
Electricity Production Costs ₹/kWh	1.59	1.48	1.46	1.62	1.46
Payment Overview					
Specific Investment Costs ₹/kWp	48000	48000	48000	48000	48000
Investment Costs ₹	74480	74480	74480	74480	74480
Savings and remuneration					
Total Utility Payment in the First Year/Year₹/Year	13084.4	14093.57	14223.4	12839.89	14226.38
Validity	2021-2046	2021-2046	2021-2046	2021-2046	2021-2046
Specific feed-in / export Remuneration ₹/kWh	5	5	5	5	5
Feed-in / Export Tariff ₹/Year	13084.4	14093.57	14223.4	12839.89	14226.385

4.4 Probability distribution P50-P90 value

The P50 and P90 values give an idea about the economic risks associated with the installation of a solar power plant. These values are a measure of the reliability of a solar project. The sponsors provide the fund generally because of P90 value, which is always lower than the P50 assessment. The probability factor also minimizes the plant risk and determine the expected energy generation in solar power plant. The role of different loss parameters, along with the solar radiation data and meteorological data, is considered while estimating the P50-P90 probability distribution.

This approach assumes that the annual yield distribution will follow a statistical law across multiple years of operation, which is supposed to be the Gaussian (or "normal") distribution. P50-P90 are different yield levels at which the probability of production exceeding this figure in a given year is 50%, and similarly for P90.

4.4.1 Comparison of P50 –P90 Value of Different Solar Module Technologies

In order to calculate P50 and P90 values, 1.58kWp multi crystalline technology, 1.68 kWp HIT technology and 1.2kWp of a-silicon technology solar power plants were used. Similar type of solar power plants were also installed in outdoor conditions for determination of the PR value in all the technologies.

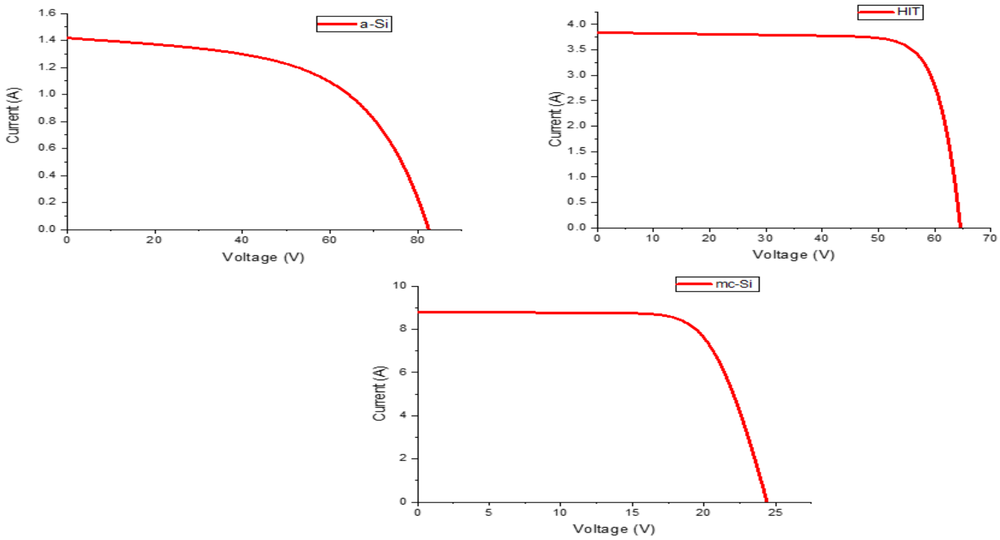


Figure 4.21 I-V curve of different three different technology (a-Si, HIT, and mc-Si) solar panels.

The simulation software “PVSYST” is used to calculate the performance ratio and P50 and P90 probability values for a-Si, HIT and mc-Si based solar power plants installed at NISE campus. Estimates of the energy amount of a solar power plant will produce in the future are crucial to decide a project’s financial risk. P50 and P90 probabilities are based on many years of historical weather data, and are useful in determination of financial issue and energy generation guarantee of solar power plants.

PVSYST simulations based on TMY datasets representing the solar resource over a multi-year period can predict the P50 and P90 value. With the help of PVSYST simulation software, P50 and P90 values may be estimated. With the help of TMY database and respective probabilities of energy generation on solar power may be calculated. P50 and P90 and P95 for a-Si technology values are found to be 1528 kWh, 1458 kWh and 1439 kWh. For the HIT technology the corresponding P50, P90 and P95 values are found to be 2698 kWh, 2576 kWh and 2541 kWh, respectively and for the mc-Si technology, the corresponding values are 2738 kWh, 2614 kWh and 2579 kWh, respectively. See Figure 4.23.

Weather parameters such as irradiance, temperature, and wind speed as well as electrical parameter such as maximum voltage, maximum current, short circuit current, open circuit voltage and maximum power affect the performance of various technology modules. The weather data and the electrical data are input to the PVSYST simulation software, which produces array yield, reference yield, system yield, collection loss, system loss, performance ratio, unused energy and P50, P90 and P95 values.

PVSYST software takes the Typical Meteorological Year (TMY) file for the simulations. TMY file is available for different locations in India. Using the right TMY file is important to predict the energy generation in the respective area. TMY file consists of long-term hourly data for each location. A particular month termed as “typical” month is chosen to represent the long-term data.

PVSYST gives access to many popular metrological data sources important for simulations. The database has some discrepancies and sometimes it is difficult to find suitable data for the particular location and error analysis. Comparison of the data from different locations, which depends upon various conditions, such as the different variable size and the climatic variability, is also an important concern in the measurement of data. Some climate change models use metrological data to predict the irradiance and temperature conditions for the future. Measurement of data using satellite images involves sophisticated models and is constantly evolving; data from satellite images helps in the analysis and validation of the ground station data. The model and techniques change from location to location. Sometimes if the required parameters, such as temperature or radiation, are not available, the data is not reliable for simulation. For avoiding these issues, comparison criteria are used: in this, annual available irradiation [kWh/m²/year] is chosen as the reference. Because the PV output is quasi-linear with the solar energy input, this value is important for PV grid systems. In the comparisons, Meteonorm 6.1 data is usually referred, which is the default data in the PVSYST database, and therefore likely to be used in any "first" simulation of a given system. PVSYST software takes the worldwide data in hourly value, synthetic generation source and period 1960-1991 and 1995- 2000. The major variables in a dataset are Global horizontal irradiance (GHI), diffuse horizontal irradiance (DHI), ambient temperature and wind velocity. In table 4.17, various sources in hourly database value are given.

Table 4.17 Sources in hourly database values

S. No.	Database	Region	Values	Source	Period	Variables
1	Meteonorm	Worldwide	Hourly	Synthetic generation	1960-1991 and 1995-2000	GHI, DHI, Ambient Temperature, Wind velocity
2	Satellite	Europe	Hourly	Meteosat (Any pixel of about 5×7 km^2)	1996-2000	GHI, No temp
3	US TMY 2/3	USA	Hourly	NREL, 1020 stations TMY	1991-2005 (samples)	GHI, DHI, Ambient Temperature, Wind velocity

4	EPW	Canada	Hourly	CWEC, 72 stations TMY	1953-1995 (samples)	GHI, DHI, Ambient temperature, Wind velocity
5	3Tier	Worldwide	Hourly	Satellites Spectroradiometer MODIS	1998-today	DHI, DNI, no, No Ambient temp

The methodology has been summarized in figure 4.22

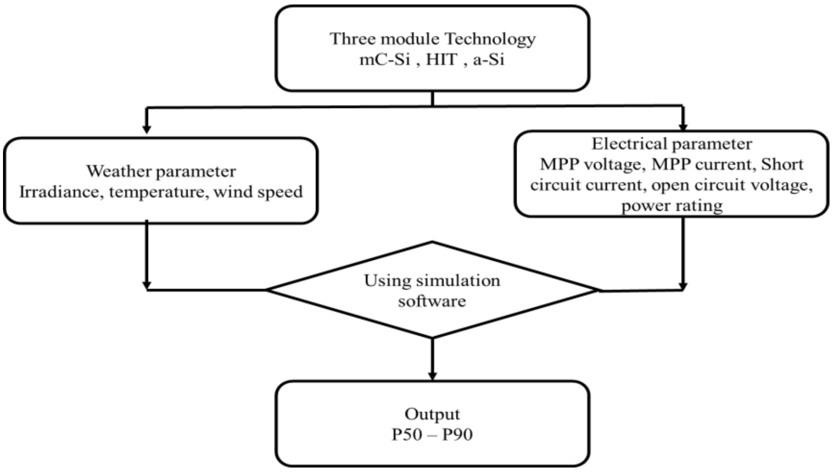


Figure 4.22 Methodology for the performance analysis

The probability distributions for the three technologies studied have been shown in Figure 4.23. These values are also given in table 4.18 for comparative analysis. From the table, we see that a-Si has lowest and mc-Si has highest P50-P90-P95 values, which means that mc-Si technology is more reliable than a-Si technology.

Table 4.18 P50-P90-P95 values of various module technologies

S. No.	**Module Technology**	**Probability Distribution (in terms of E_{grid} system production in kWh)**		
		P50	**P90**	**P95**
1	a-Si	1528	1458	1439
2	HIT	2698	2576	2541
3	mc-Si	2738	2614	2579

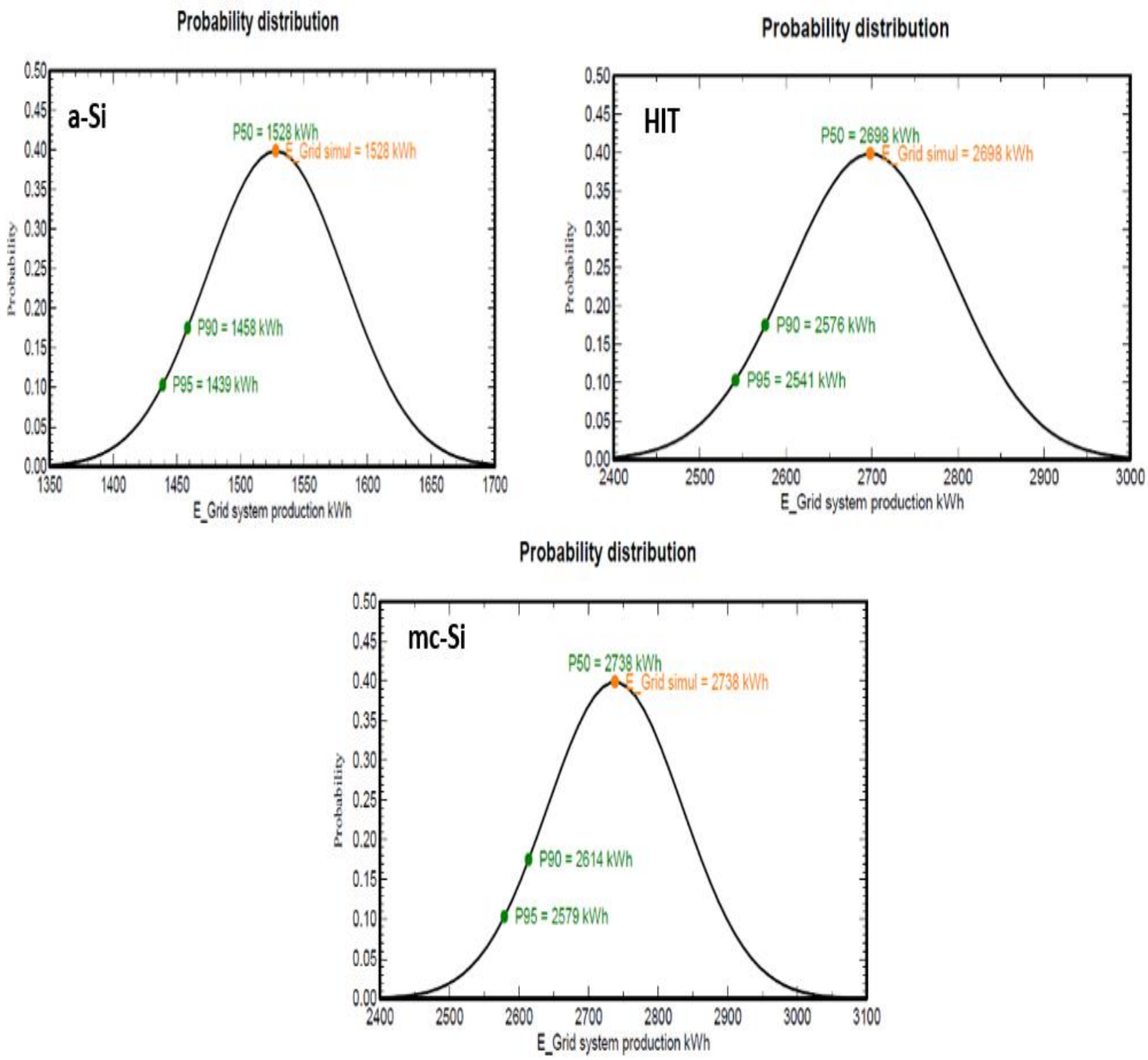


Figure 4.23 Probability distributions for a-Si, HIT and mc-Si technologies

4.5 Prediction of module temperature from weather parameters using ANN.

At a time when conventional energy sources are being depleted, photovoltaic (PV) conversion of solar energy appears to be the most viable approach of fulfilling future energy demands. Despite the fact that solar energy is an infinite source of energy, the energy output of a PV module (which converts solar energy to electrical energy) is inextricably linked to meteorological conditions such as irradiance, relative humidity, wind speed, ambient temperature, and so on. Understanding how PV output is affected by various weather variables can aid us in setting realistic targets for non-conventional renewable energy production. Module temperature is the most critical observable that impacts the power output of a PV panel, and it is dependent on different meteorological conditions as described above. With this goal in mind, the current study focuses on developing a mathematical model using the Artificial Neural Network (ANN) scheme to predict module temperature using real-time field data of various parameters recorded at India's National Institute of Solar Energy (NISE), which is located in a composite climatic zone. The comparison of temperature obtained from the ANN model and the temperature recorded by the sensors deployed in the PV panels shows an overall coefficient of correlations (R) of about 99.16% and a regression coefficient (R^2) of 98.34 %. These results indicate that ANN can be useful in generating good predictions based on completely unknown data consisting of several variables, which can be used to learn solar energy's potential for any geographical location.

The module data was obtained from National institute of Solar Energy (NISE), Gurugram, India. The PV system consisted of a combination of 4 series and 4 parallel amorphous- silicon modules of 75-watt power each, providing a net power of 1200 Watt. The module data is provided in Table 1. Using the above set up, a yearly data of 2010, comprising of variable weather parameters, was recorded. The data was sampled every 10 minutes and averaged for every hour. The data was recorded for five input and one output parameters: solar irradiance (I_{rr}), relative humidity (RH), wind speed (WindSpd), wind direction (WindDir) and ambient temperature (T_{ambient}). The one output parameter was the module temperature (T_{module}), which is the target temperature (or the output) for neural network model. In the model, solar irradiance is measured in watt/m^2; wind speed is measured in m/s; wind direction has been taken in North azimuth degree (°); the temperatures (ambient and target) are measured in °C, and relative humidity is measured in percentage (%) from 0 to 100%.

Method of Data analysis

A Neural model, using single perceptron model, was developed using Matlab® R2017b. The data obtained from NISE consisted of several inputs and the target. The goal was to develop a mathematical link between the module target temperature and weather-related parameters (irradiance, humidity, wind speed, wind direction, and ambient temperature), which was expressed in the form of following equation:

$$T_{\text{module}} = (w_1 I_{\text{rr}} + w_2 \text{RH} + w_3 \text{WindSpd} + w_4 \text{WindDirec} + w_5 T_{\text{ambient}}) + \text{constant}$$

The data consisted of points being sampled and recorded after every 10 minutes for the entire year 2010 (January- December). The data count, hence, was enormous. As a result, the data was segregated and averaged based on the months. It was done in order to simplify and reduce the error for modelling our neural network. The network was divided into three segments, as is customary in an ANN system: training set, validation set, and testing set. The training set is used to fine-tune the neural network's weights. To avoid over-fitting, a validation set is utilised. With this data set, we're not altering the network's weights; instead, we're ensuring that any improvement in accuracy over the training data set is also an increase in accuracy over a data set that the network hasn't seen before, or at least hasn't been trained on (i.e. validation data set). If the accuracy of the training data set improves but the accuracy of the validation data set remains the same or declines, the neural network is overfitted and training should be stopped. The testing set is only used to test the final solution and check the network's true predictive power. Based on a comparison of the output and the target, the network was changed until the network output matched the target. We keep training and developing a relationship between the target and the output until the ANN training plot shows high R (coefficient of correlations) values. To acquire the best result, we also adjust parameters like epochs and aim. In order to confirm the effectiveness of our model, a linear regression curve was generated to compare the neural output temperatures with the target module temperature. Based on five inputs: solar irradiance, relative humidity, wind speed, wind direction, and ambient temperature, an ANN strategy was created to predict PV module temperature. We used Matlab's Neural Network Toolbox to estimate the unknown parameters and their interactions. A correlation curve (Figure 4.24) was obtained from the neural training sets with R^2 value of 90.3 % for training set, 96.9% for validation set, 90.4 % for test set, with an overall correlation of 90.76 %. These correlations correspond to a successful neural training and testing of our model. Figure 4.24 is generated by neural network toolbox in which the temperature (°C) computed from the trained neural model has been plotted on y axis, and the panel temperature recorded at NISE (target temperature) has been plotted on x axis.

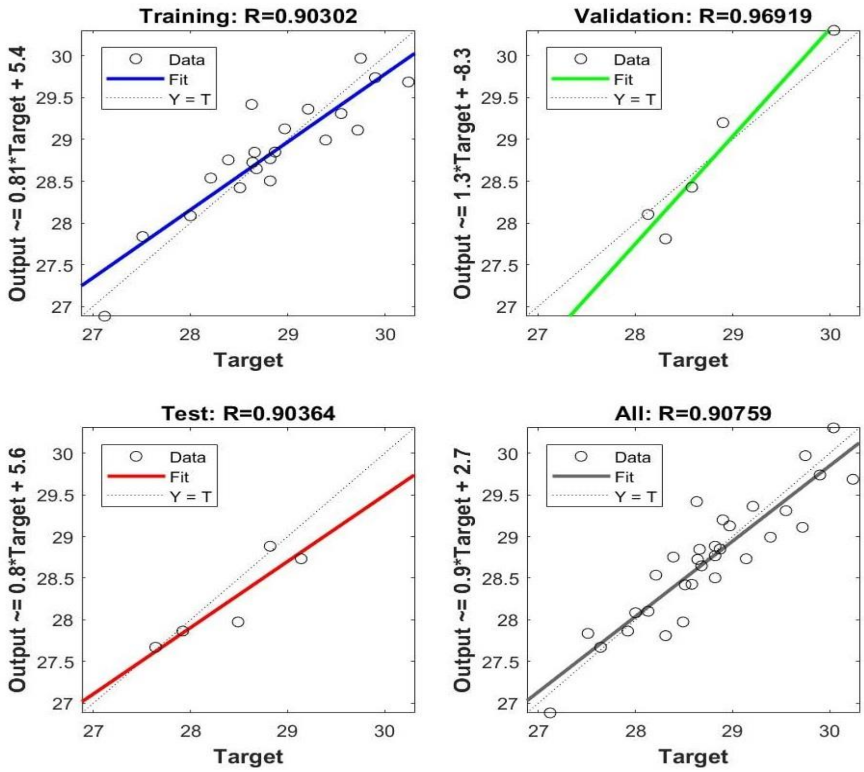


Figure 4.24 ANN Correlation analysis, depicting Training set, Validation set, Test set and overall comparison. The label on y axis is the temperature (°C) computed from the trained neural model and the label on the x axis is the temperature recorded at NISE (target temperature).

The performance plot (see Figure 4.25) has been prepared to show how the mean squared error (MSE) drops rapidly as the network learns from the data.

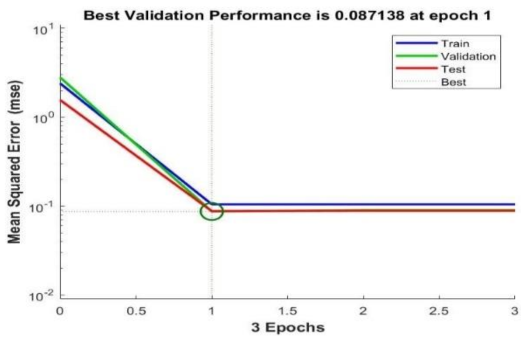


Figure 4.25 ANN Performance Plot (Mean Squared Error vs Epoch plot

The diminishing inaccuracy in the training data is depicted by the blue line in the figure. The figure's green line depicts the progression of validation error throughout epochs. When the validation error stops reducing, training comes to an end. The inaccuracy on the test data is shown in red, demonstrating how well the network will adapt to new data. The weights acquired from the network, as indicated in Table 4.19, correspond to the input parameters coefficients.

Table 4.19 Weights obtained from ANN model

Corresponding Weights	Parameter	Weight values
W_1	Solar irradiance	+ 0.14
W_2	Relative humidity	- 0.86
W_3	Wind speed	-0.32
W_4	Wind direction	-0.07
W_5	Ambient temperature	+0.26

The linear regression curve has been plotted between the target module temperature and neural output temperature (see Figure 4.26). R- Squared (R^2) values have been used for the regression analysis. R- Squared value is a statistical measure, which tells the closeness of the data to the fitted linear regression line. A R^2 value of 0% indicates there is no linear relationship between x- and y- axis values and hence a bad fit, whereas R^2value of 100 % value indicates a perfect fit between them. The R^2value obtained in our neural model was found to be 98.34 %, which establishes a very good fit of our model with the data.

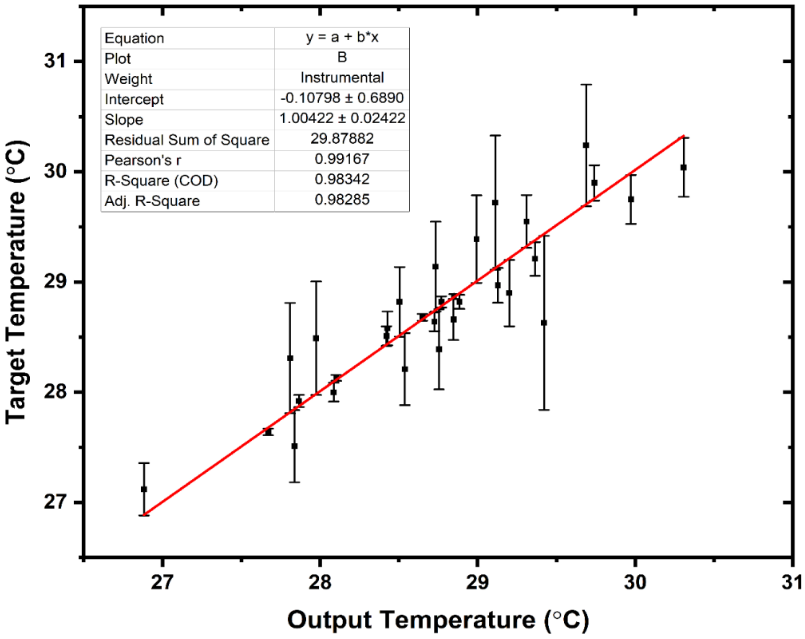


Figure 4.26 Linear regression plot between neural Output temperature (x- axis) vs measured Module temperature (y- axis). Error bar is shown.

The final equation that was obtained as per the network is:

$$T_{\mathrm{module}} = \left(0.14\, I_{\mathrm{rr}} - 0.86\mathrm{RH} - 0.32\ \mathrm{WindSpd} - 0.07\ \mathrm{WindDirec} + 0.26\, T_{\mathrm{ambient}}\right) - 0.11$$

where the unit for T_{module} and T_{ambient} are in °C, I_{rr} is watt/m^2, RH is in %, Wind Speed is in m/s and Wind Direction is in degrees (°).

Above equation help us to understand the simultaneous relationship between PV panel efficiency and meteorological conditions. The weights/coefficients in the model quantify the impact of various meteorological conditions on PV panel temperature. The results demonstrate that the module temperature has a positive relationship with irradiance and ambient temperature, but has a negative relationship with humidity, wind speed, and wind direction.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

CONCLUSION

Understanding the performance of different types of SPV technologies in various climatic zones / conditions is very important from the perspective of installation of a particular technology module in a particular climatic zone. Installation of a technology with optimum performance vis-à-vis the climatic conditions may prove to be economically feasible and will have a longer lifetime.

Keeping the above in mind, outdoor performance analysis of various technology PV panels like HIT, CdTe, mc-Si, a-Si, IBC, CIGS has been done using PVSOL, PVSYST software's and the simulated results have been validated against the performance estimated using field data obtained from different test bed setups installed physically at NISE campus, Gurugram. Performance ratio (PR) has been used as a metric to determine the performance of the technologies. Based on the PR values in different climatic zones, the suitability of a particular technology has been proposed. Financial aspects of these technology panels have also been researched for different climatic zones in India. Thereafter, ANN scheme is used to establish the relation between various input parameters (weather data, ambient temperature, solar irradiation, etc.) and the module temperature, since module temperature invariably affects the performance of the panels from a fundamental perspective.

Performance and reliability behavior of different types of SPV technologies in composite as well as other climatic conditions is very important from the point of point of view of selection and installation of a particular technologies module in a particular climate. The technologies performing better in a particular region may provide the economic feasibility in terms of return on investment and other metrics.

The present investigation may help in prediction of outdoor performance and for the selection of best SPV module technologies in composite climatic condition. The main outcomes of this research from the industry point of view are:

- For the manufactures – this research may be helpful in selection of the best material quality of PV modules.

- For the promoters – The outcome of this research work may provide relevant information about the technology and how they perform under different climatic conditions.
- For installers – The research may help in understanding the cost effectiveness in installation and operational maintenance.
- For Government – This research may also be helpful in solar policy improvement and skill enhancement training activities.
- For customers – The customers may know a priori the performance and reliability of the modules before using the technologies.

There is a greater need for manufacturing equipment’s in the renewable energy sector in order to support Government of India's renewable energy objective. This objective will need trained work force in installation, system design, operations & maintenance, financing, and marketing. The demand in this sector therefore led to creation of numerous jobs in the field of renewable energy, such as solar energy, wind energy, and offshore wind, etc. Recent graduates are not the only ones who find this career path intriguing; those who are already employed in other energy industries like oil and gas also find it appealing. Simply said, more money is being spent on developing sustainable energy solutions, which is why there are so many new jobs being generated in renewable energy. Governments are investing more in renewable energy technologies and some even give tax breaks to people who purchase such technologies as solar panels. India's growing energy demand problems can be greatly alleviated by the use of renewable energy sources. Furthermore, as evidenced in more developed markets, renewable energy technologies are more labor-intensive than highly mechanized fossil fuel technologies, and thus can offer a huge chance to create local jobs. The future of global energy production will heavily rely on renewable energy sources like offshore wind and solar energy. One may actively participate in a worldwide movement by supporting the creation and use of renewable energy sources.

Recommendation for Future Work

As there are thousands of researchers working in this sector, many new patterns are emerging. Here are some fresh fashions:

1. Energy storage solutions: As renewable energy source do not provide continuous energy, the electrical energy produced needs to be stored for consumption when the source of energy is unavailable. There is lot of scope in developing smart storage devices which could have very energy density, last longer, less costly and sustainable. .

2. Microgrids: Microgrids are relatively new systems for producing, transferring, and distributing renewable energy. This is getting traction due to being less complex, needs less maintenance, etc.

3. Lower cost of energy production: In order to make renewable sources as main source of energy consumption, per unit cost of energy production should go down. The development of low-cost equipments employed in energy production via SPV should be worked upon. Lowering of energy production cost may also be done if we use recyclable materials..

4. Artificial Intelligence (AI) and Internet of Things (IoT): With the help of AI and IoT, managing every aspect of a plant is getting simpler. As a result, electricity generation and plant operations have becomes comparatively efficient and cost effective.

5. Data Science & Data Analytics: Like many other industries, the energy sector is also undergoing a transformation thanks to data science, machine learning, and big data analytics, which are lowering costs and enabling energy producers to respond to market demands. In order to reduce the price of solar energy and expand the markets for its technologies, the solar sector needs to quickly adopt novel methods of data science.

PUBLICATIONS FROM THE CURRENT RESEARCH WORK

1- **Yogesh Kumar Singh**, Pramod Rajput, Maria Malvoni, O. S. Sastry, Santosh Dubey*, Kailash Pandey Assessment of Losses in Cadmium Telluride and Micromorph Based Thin Film Photovoltaic Systems under Real Operating Conditions AIP Conference Proceedings 2276, 020049 (2020).

2- **Yogesh Kumar Singh**, S. Dubey*, K. Pandey , O.S.sastry Performance of HIT module in different climatic condition in India Materials Today: Proceedings Volume 17, Part 1, 2019, Pages 321-328.

3- Anish H. Verma, Santosh Dubey*, **Yogesh K. Singh**, Santosh K. Joshi A neural network model of PV module temperature as a function of weather parameters prevailing in composite climate zone of India International Journal of Ambient Energy 2021

4- **Yogesh Kumar Singh**, Kailash Pandey, Santosh K. Joshi, Santosh Dubey*, O. S. Sastry Performance Assessment of Different Photovoltaic Module Technologies Under Novel Climatic Conditions in India Journal of Solar Energy Engineering (Under Review with IEEE Transactions on Sustainable Energy).

5- **Yogesh Kumar Singh** , Kailash Pandey, Santosh Dubey*, and O.S. Sastry Comparison Of P50 –P90 Value Of Different Solar Module Technologies Journal of Solar Energy Engineering (Under Preparation)

6- Pramod Rajput, **Yogesh Kumar Singh**, G.N. Tiwari, O.S. Sastry, Santosh Dubey, Kailash Pandey Life cycle assessment of the 3.2 kW cadmium telluride (CdTe) photovoltaic system in composite climate of India Solar Energy 159 (2018) 415–422.

7- Rahul Rawat, S. C. Kaushik O. S. Sastry Birinchi Bora, **Y. K. Singh** Long-term Performance Analysis of CdTe PV module in real operating conditions Materials Today: Proceedings 5 (2018) 23210–23217

8- Rahul Rawat, S.C. Kaushik , O.S. Sastry, **Y.K. Singh**, B. Bora Energetic and exergetic performance analysis of CdS/CdTe based photovoltaic technologies in real operating conditions of composite climate Energy Conversion and Management 110 (2016) 42-50.

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