Techno-Economic Analysis of Monocrystalline & Polycrystalline PV Modules in Different Climatic Zones of India

A THESIS SUBMITTED TOWARDS PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE
OF

Master of Technology
In
Energy Science and Technology

Course Affiliated To
Faculty of Engineering and Technology
Under

Faculty Council of Interdisciplinary Studies
Law & Management

Jadavpur University

Submitted By

DEBANJAN BAGUI

Examination Roll No: M4ENR23003

Registration No: 160460 of 2021-2022

Under The Guidance Of

Dr. RATAN MANDAL
Supervisor, Professor and
Director

School Of Energy Studies
Jadavpur University
Kolkata–700032
India

2023

M.Tech Energy Science & Technology
Course affiliated to
Faculty of Engineering & Technology
Under
Faculty Council of Interdisciplinary Studies
Law & Management,Jadavpur University
Kolkata, India

CERTIFICATE OF RECOMMENDATION

This is to certify that the thesis entitled "**Techno-Economic Analysis of Monocrystalline & Polycrystalline PV Modules in Different Climatic Zones of India**" is a bonafide work carried out by **Mr. Debanjan Bagui** under our supervision and guidance for partial fulfillment of the requirements for the Post Graduate Degree of Master of Technology in Energy Science and Technology, during the academic session 2021-2023.

THESIS SUPERVISOR
Dr. RATAN MANDAL
Director and Professor
School of Energy Studies
Jadavpur university
Kolkata–700032

DEAN
Faculty Council of Interdisciplinary Studies,
Law and Management
Jadavpur University
Kolkata–700032

M.Tech Energy Science & Technology
Course affiliated to
Faculty of Engineering & Technology
Under
Faculty Council of Interdisciplinary Studies
Law & Management,Jadavpur University
Kolkata, India

CERTIFICATE OF APPROVAL

This foregoing thesis is hereby approved as a credible study of an engineering subject carried out and presented in a manner satisfactory to warranty its acceptance as a prerequisite to the degree for which it has been submitted. It is understood that by this approval the undersigned does not endorse or approve any statement made or opinion expressed or conclusion drawn therein but approves the thesis only for the purpose for which it has been submitted.

Committee of --------------------------------------

The final examination for ---------------------------------------

Evaluation of Thesis ---------------------------------------

DECLARATION OF ORIGINALITY AND COMPLIANCE OF ACADEMIC ETHICS

I hereby declare that this thesis contains a literature survey and original research work by the undersigned candidate, as part of his Master of Technology in Energy Science and Technology studies during the academic session 2021-2023.

All information in this document has been obtained and presented in accordance with academic rules and ethical conduct.

I also declare that, as required by these rules and conduct, I have fully cited and referred all materials and results that are not original to this work.

Name	**: Debanjan Bagui**
Examination Roll No.	**: M4ENR23003**
Thesis Title	**:Techno-Economic Analysis of Monocrystalline & Polycrystalline PV Modules in Different Climatic Zones of India**
Signature	**:**
Date	**:**

ACKNOWLEDGEMENTS

I feel honored to express my deepest respect, reverence, indebtedness, and heartiest gratitude to my respected supervisor Professor Dr. Ratan Mandal (Director, School of Energy Studies, Jadavpur University) for his acute interest in each and every detail of this project, judicious guidance, constant inspiration and help during the entire period of execution of the present project work.

I am also grateful to Dr. Tushar Jash (Professor, School of Energy Studies, Jadavpur University), Deepanjan Majumder,and Tarak Nath Chell for their valuable advice and encouragement during the period of the project work.

I am also grateful to all my classmates especially Mr. Arnab Jyoti Mondal, and all staff members of the department for their constant motivation and assistance during the project.

Finally, I want to thank my parents who have supported me in every ups and downs of my life and have encouraged me all the time without expecting anything in return.

DEBANJAN BAGUI

Examination Roll No: M4ENR23003

Registration No: 160460 of 2021-2022

School of Energy Studies

Jadavpur University

Kolkata–700032

NOMENCLATURE

AM	Air Mass
a-si	Amorphous Silicon
CdTe	Cadmium Telluride
CIGS	Copper Indium Gallium Diselenide
c-Si	Crystalline Silicon
DHI	Diffuse Horizontal Irradiation
DSSC	Dye Synthesized Solar Cell
FY	Full-Year
GaAs	Gallium Arsenide
GHI	Global Horizontal Irradiation
HIT	Hetero-junction with Intrinsic Thin-layer
LCOE	Levelized Cost of Energy
LGBC	Laser Grooved Buried Contact
mc-Si	Multi Crystalline Silicon
MNRE	Ministry of New and Renewable Energy
m-Si	Monocrystalline Silicon
OPEC	Organization of the Petroleum Exporting Countries
PR	Performance Ratio
p-Si	Polycrystalline Silicon
PV	Photovoltaic
QD	Quantum Dot
R/P	Reserve Vs. Production
ROI	Return on Investment
STC	Standard Test Condition
Wp	Watt Peak

CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter-1

Introduction

1.1 Introduction

In modern days, one of the most significant & desired requirements for all developed and developing countries is energy. Even if there are various methods of energy production and consumption, all countries require cheap, large, and clean energy sources [1]. The consumption of energy is increasing rapidly whereas the available resources remain limited. The global need for energy is increasing on average by 2.4% every year [2]. Out of the total consumed energy, around 85% of energy comes from fossil fuels [2]. With this consumption scenario, there will be no fossil fuel left for us to use in the future. Energy consumption also has a significant impact on the environment. Excessive usage of fossil fuels as the main energy source has become the main factor that contributes to global warming. Carbon dioxide (CO_2) & carbon monoxide (CO) emissions from the combustion of fossil fuels increase the temperature of the atmosphere. For any developing country, the energy or power sector needs huge investments to meet the expectation of the ever-increasing energy demands. To maintain the growth rate of energy we need to shift from our conventional source of energy (petroleum, natural gas, coal, electricity, etc.) to renewable energy (solar, hydro, wind, biomass, etc.), which are sustainable and environmentally friendly.

1.2 Concept of Energy

Any kind of physical activity whether it is performed by any human being or by nature, causes the transfer of energy from one form to another. The word ‘energy’ originated from the Greek word ‘en-ergon’, which defines ‘in-work’ or ‘work content’. Since the work output depends on the input, hence energy can be considered as one of the leading building blocks for the economic development of any country.

1.3 Classifications of Energy

Energy can be classified into several types based on the following criteria (Figure-1.1)

- ➔ Primary and Secondary Energy
- ➔ Commercial and Non-Commercial Energy
- ➔ Renewable and Non-Renewable Energy
- ➔ Conventional and Non-conventional Energy

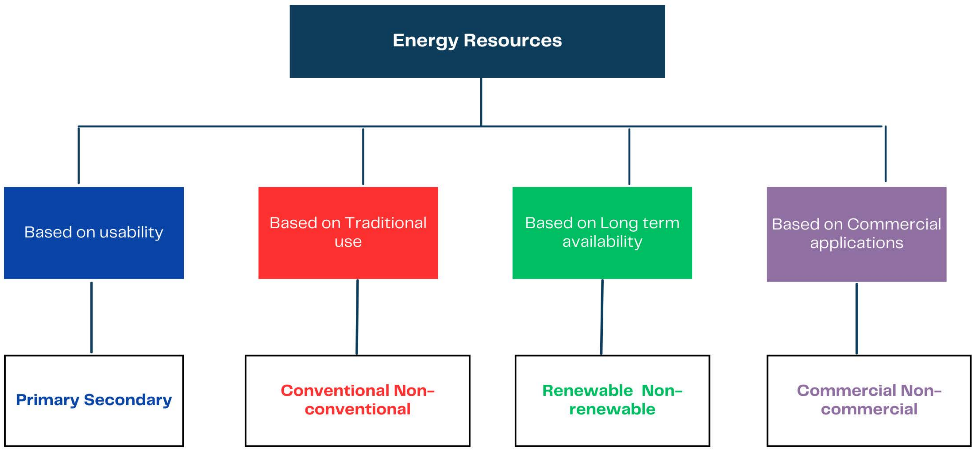

Figure 1.1 Classification of Energy Resources

1.3.1 Primary Energy

Primary sources of energy can be defined as the energy source which is either found or stored in nature & can be used directly without any type of modification. The most common example of primary energy sources are coal, oil, natural gas, biomass, nuclear energy from radioactive substances, thermal energy stored in the core of the earth, gravitational potential energy, etc. Primary energy can be further divided into two distinct groups

- ➔ Renewable Energy (Wind, Solar, Geothermal, Hydro, etc.)
- ➔ Non-renewable Energy (Coal, Natural Gas, Oil Fossil Fuels, Nuclear, etc.)

The primary energy content of all fuels is generally expressed in terms of the tonne of oil equivalent.

1.3.2 Secondary Energy

The more convenient form of converted energy from primary energy sources is known as secondary energy. Primary energy is mostly converted into secondary energy sources due to industrial utilities & use cases, for example, petrol is obtained from crude oil, electric energy is obtained from thermal power plants by using coal as fuel, etc. Primary energy can also be used directly, for example, coal or natural gas can be used as a feedstock in fertilizer plants.

1.3.3 Commercial Energy

The energy which is available in the global market for a certain price rate is known as commercial energy. Irrespective of the method of the production of energy, whether it is from fossil fuels, nuclear or renewable sources, any form of energy used for commercial purposes is termed as commercial energy. The most important forms of commercial energy are coal, refined petroleum products, natural gas, and electricity. Commercial energy is the building block of agricultural, industrial, commercial, and transport development in modern days. For every country, whether it is developing or developed, commercialized fuels are the backbone of economic development for a country.

1.3.4 Non-Commercial Energy

The energy sources that are generally free to use and does not available in the commercial market for a price are known as non-commercial energy. This form of energy is used for domestic consumption purposes. It includes fuels such as firewood, cattle dung, and agricultural wastes, which are traditionally gathered, and not bought at a price used especially in rural areas. These are also known as traditional fuels. Examples of non-commercial fuels are solar and wind energy for electricity generation, agro waste, animal-powered transport, etc.

1.3.5 Renewable Energy

The energy those are comes from natural sources & constantly refilled by nature is known as renewable energy. Such as solar energy, wind energy, hydroelectric, and geothermal energy. The two most important features of renewable energy are that it can be harnessed without the release of harmful pollutants and unlimited availability in nature. These can be renewed over a relatively short period compared to fossil fuels. These include firewood from the forest, petro plants, plant biomass, agricultural waste like animal dung, solar energy, wind energy, water energy in the form of hydroelectricity and tidal energy, geothermal energy, etc.

1.3.6 Non-Renewable Energy

Non-renewable energy is considered as a natural source of energy that cannot be reproduced, grown, or used in such a way that can sustain its consumption rate. The consumption rate of these resources is faster than the production rate, natural resources like oil, natural gas, and coal take millions of years to form and they cannot be replaced as fast as they are being consumed nowadays. As a result, these resources will be drained with time.

1.3.7 Conventional Energy Sources

The sources of energy which are used since the beginning of mankind such as petroleum, natural gas, coal, and water power are known as conventional energy. They are exhaust able except for water and cause pollution when used, as they emit smoke and ash.

1.3.8 Non-Conventional Energy Sources

The source of energy which are still in the process of development over the past few decades such as wind, solar, geothermal, and biomass are known as non-conventional energy. They are inexhaustible, pollution free, easy to maintain, and less expensive compared to conventional energy sources.

1.4 Global Fossil Fuels Reserves

1.4.1 Coal Reserves

World coal reserves in 2020 were at 1074 billion tonnes and are heavily concentrated in the following countries US (23%), Russia (15%), Australia (14%), and China (13%). Most of the reserves coals are anthracite and bituminous (70%) types. Based on the current global R/P ratio the coal reserves in 2020 accounted for 139 years of the current production rate [3]. Figure-1.2 shows the reserves scenario of coal in 2000, 2010, and 2020 respectively.

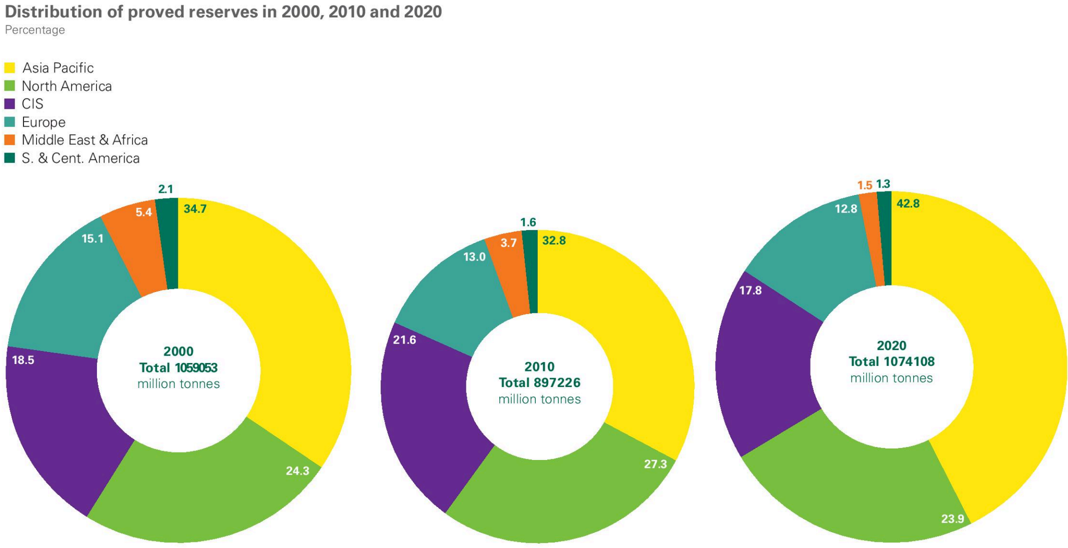

Figure 1.2 Coal Reserves Scenario

1.4.2 Oil Reserves

Globally proved oil reserves were near about 1732 billion barrels at the end of the year 2020. Based on the current global R/P ratio the oil reserves in 2020 accounted for nearly about 50 years of current production. OPEC holds 70.2% of global reserves [3]. The world's top countries in terms of oil reserves are Venezuela (17.5%), Saudi Arabia (17.2%), and Canada (9.7%). Figure-1.3 shows the reserves scenario of oil in 2000, 2010, and 2020 respectively.

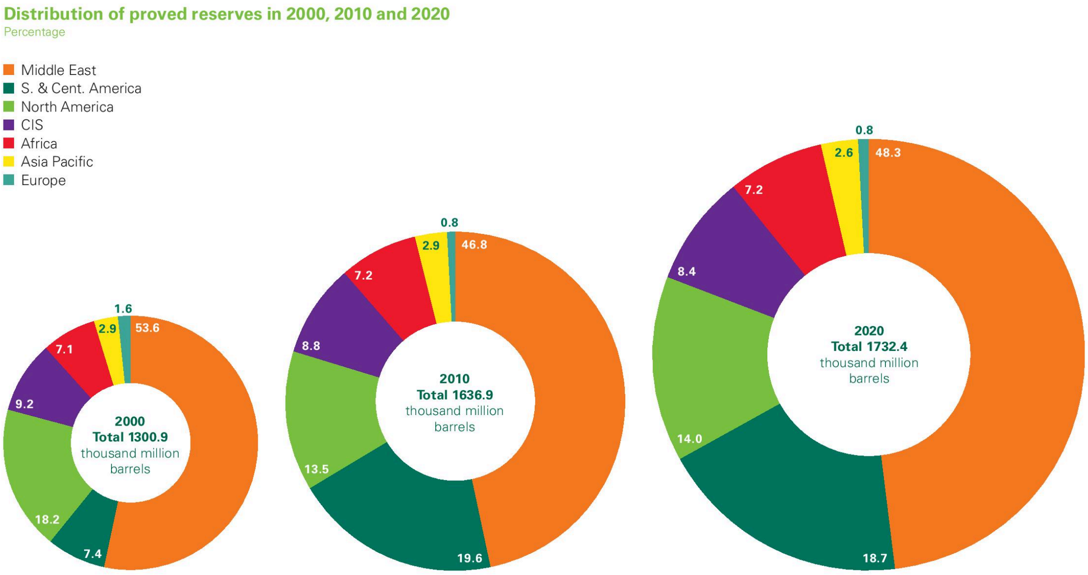

Figure 1.3 Oil Reserves Scenario

1.4.3 Natural Gas Reserves

Globally proved natural gas reserves were near about 188.1 Tcm in 2020. The largest natural gas reserves in terms of countries are Russia (37 Tcm), Iran (32 Tcm), and Qatar (25 Tcm). Based on the current global R/P ratio the gas reserves in 2020 accounted for 48.8 years of current production. The Middle East (110.4 years) and CIS (70.5 years) are the regions with the highest R/P ratio [3]. Figure-1.4 shows the reserves scenario of oil in 2000, 2010, and 2020 respectively.

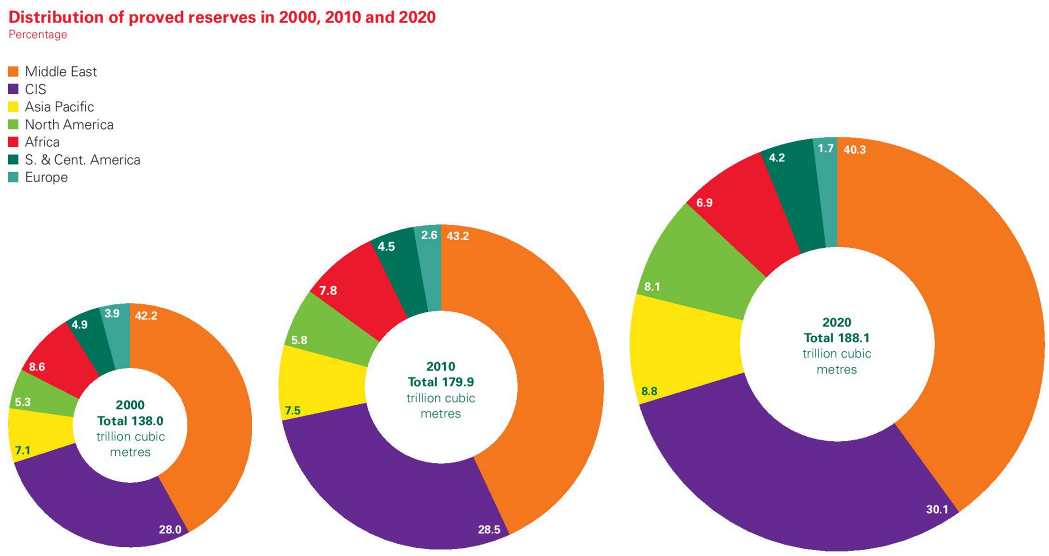

Figure 1.4 Natural Gas Reserves Scenario

1.5 Global Fossil Fuels Consumption Statistics

Primary global energy consumption grew by 5.5% in 2021 compared to 2020 to a new all-time high. In 2020 there is a huge dip in energy consumption due to COVID-19 but since everything is back to normal the energy consumption is increasing day by day. Figure-1.5 represented the fastest energy consumption growth since the early 2000s and is a reflection of strong global demand bouncing back from 2020's COVID-19 energy consumption decline. Almost 82% of primary energy use for 2021 accounted for Fossil fuels, in terms of which coal (26.9 %), oil (31.0 %) & natural gas (24.4%). The remaining share of primary energy use consisted of hydroelectric power (6.8%), renewables (6.7%), and nuclear power (4.3%) [3]. Figure-1.6 represents the worldwide primary energy consumption based on per capita [4].

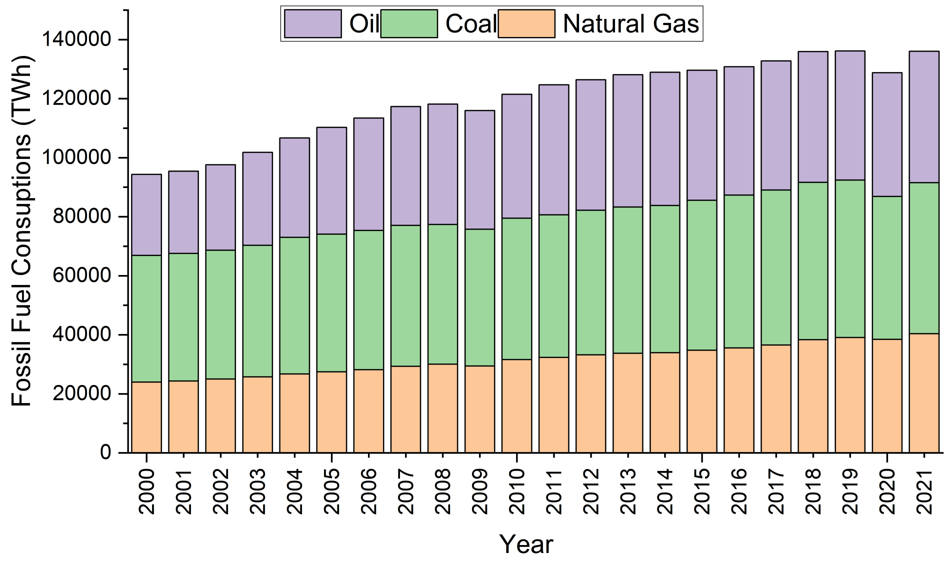

Figure 1.5 Worldwide Fossil Fuels Consumption Scenario

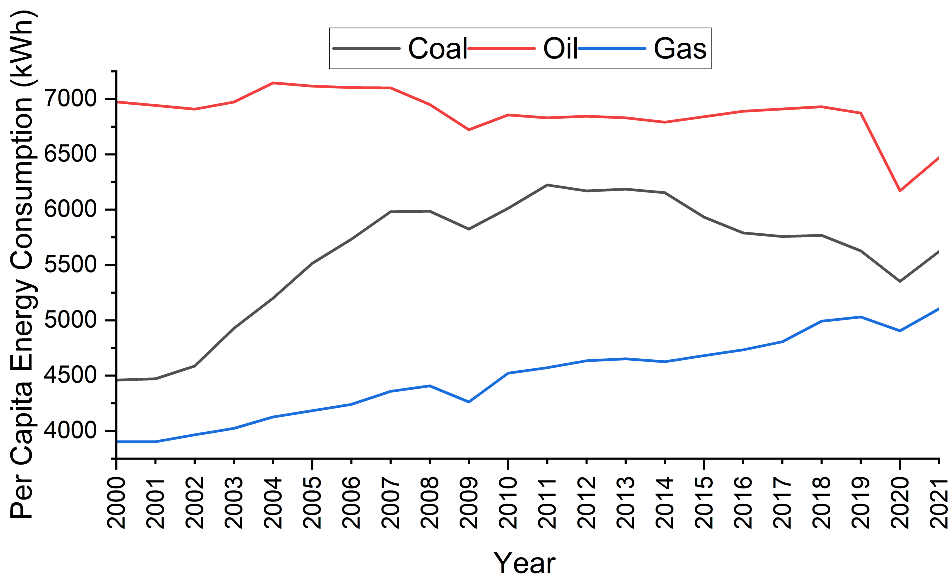

Figure 1.6 Worldwide Per Capita Energy Consumption Scenario

1.6 Fossil Fuels Reserves in India

1.6.1 Coal Reserves

Total estimated reserves of coal as of 01-04-2022 were 361.41 billion tonnes, an addition of 9.28 billion tonnes compared to the previous year. In terms of the percentage the available coal for extraction considering the economic viability, feasibility study, and geologically exploration level, is almost 52%. Figure-1.7 shows the total estimated reserves of coal in India as of 01-04-2022 [5].

1.6.2 Oil Reserves

The estimated reserves of crude oil in India as of 01-04-2022 were 651.77 million tonnes. The geographical distribution of crude oil in the Indian subcontinent shows that the maximum reserves are in the western sides of the country almost 33% followed by Assam (23%). Figure-1.8 Shows the state-wise total estimated reserves of oil in India as of 01-04-2022 [5].

1.6.3 Natural Gas Reserves

The estimated reserves of natural gas as of 01-04-2022 were at 1138.67 billion cubic meters. The maximum reserves of natural gas are in the western offshore at 29.6% followed by the Eastern offshore at 23.6%. Figure-1.9 Shows the total estimated reserves of natural gases in India as of 01-04-2022 [5].

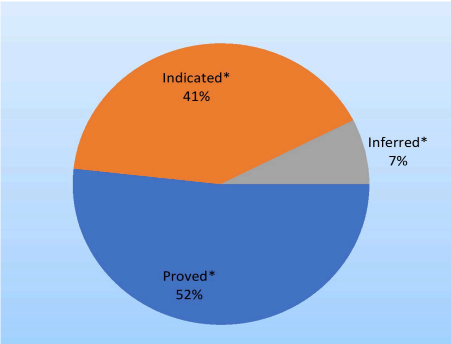

Figure 1.7 Total Estimated Coal Reserves in India as of 01-04-2022

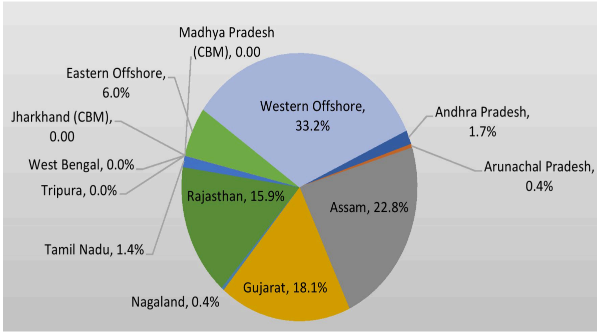

Figure 1.8 Total Estimated Oil Reserves in India as of 01-04-2022

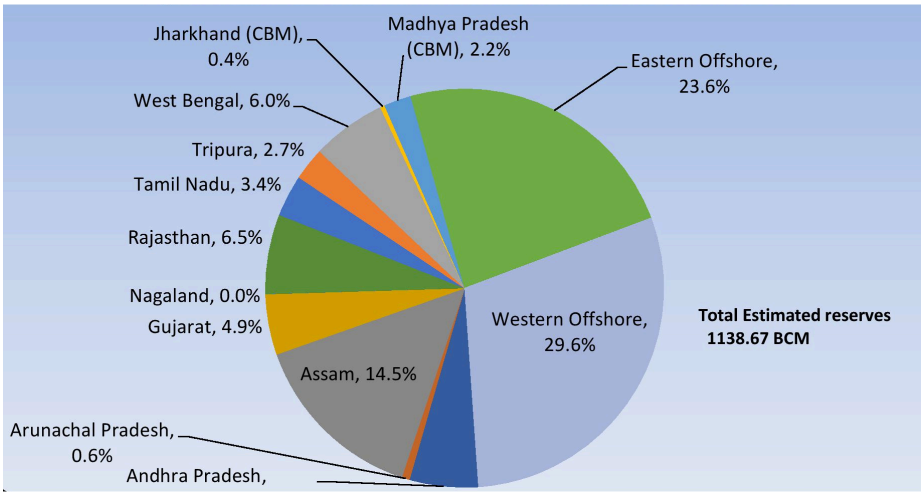

Figure 1.9 Total Estimated Natural Gas Reserves in India as of 01- 04-2022

1.7 Fossil Fuels Consumptions in India

During the FY 2021-22, India along with the world experienced a very slow rate of energy consumption, due to the COVID-19 pandemic, where all the sectors experienced a negative growth rate. But in this FY since everything is back to normal all the sectors have come up with a healthy growth rate indicating a steady recovery of the Indian economy. Figure-1.10 represents Energy consumption statistics from 2000 to 2021[4]. From the figure, we can see that throughout the year the energy consumption rate kept increasing where the maximum percentage of primary energy consumed in the form of oil. Figure-1.11 shows a comparison of the per capita energy consumption of India along with some other developed countries [4]. Looking at the graph one can conclude that the per capita energy consumption in India is less compared to other developed countries so we don't need to care about the energy consumption rate and energy security but in the real scenario, we need to remember two things first India is still a developing country means the per capita energy consumption will grow day by day and the other point is the population of India which is way larger than other countries, even according to the latest survey India is the most populated country in the world [6].

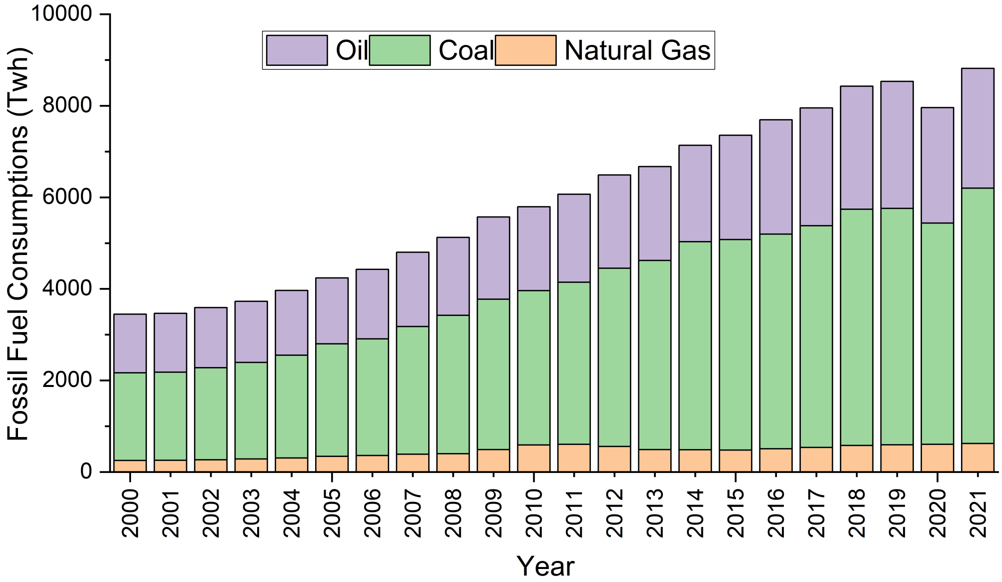

Figure 1.10 Total Energy Consumptions by Sources in India

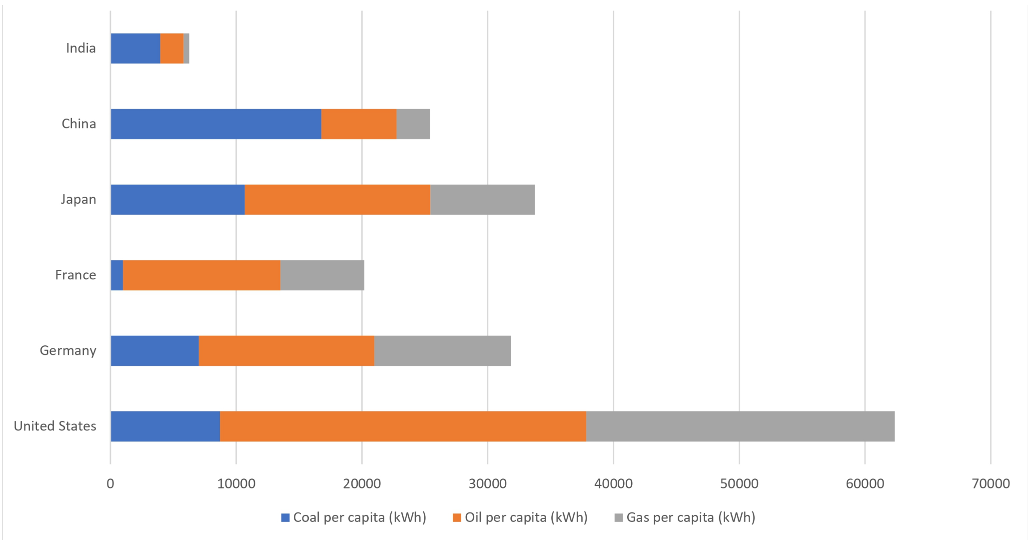

Figure 1.11 per Capita Energy Consumption Comparison

1.8 Need for Renewable Energy

Considering the above R/P ratio of India there is a serious concern about the energy demand & security in India. The amount of energy required is different between the countries around the world. The developed country needs more energy compared to the developing country. As India moves toward a developed country, energy requirements will remain very intensive. At present, almost half the energy consumption in the nation is consumed by the industrial, residential, and commercial sectors [7]. The energy sector is one of the important keys for economic development, there is a strong relationship between economic growth and energy consumption. Different countries have different sources of renewable energy. The developed countries are additionally resembling to apply renewable energy technology for job opportunities. In the present situation, people are more dependent upon fossil fuel energy sources. It is generally costly and environmentally damaging. Due to the combustion of fossil fuel, huge amounts of Carbon dioxide (CO_2) and Carbon Monoxide (CO) are emitted which is one of the main reasons for the greenhouse effect, hence global warming occurs. Figure-1.12 shows the CO_2 emission statistics over the years [8]. The availability of fossil fuels such as coal, crude oil, etc. Are usually limited hence it is necessary to focus the other energy sources as well. Nowadays people are more concerned about renewable energy sources because of their availability, cost-efficient & pollution-free nature. In renewable energy technology, we use natural sources of energy for example, solar radiation energy, wind energy, tidal energy, biomass energy, geothermal energy, etc. These energy sources are environmentally friendly and freely available in nature. The main opportunities we are getting from the use of renewable energy sources are social and economic development, more energy security, climate change reduction, and improving environmental and health energy. According to a global survey Indian renewable energy sector is the fourth most diverse renewable energy market in the world [8]. The Indian government is prioritizing the use of clean energy sources by undertaking various large-scale renewable power projects and by promoting green energy highly.

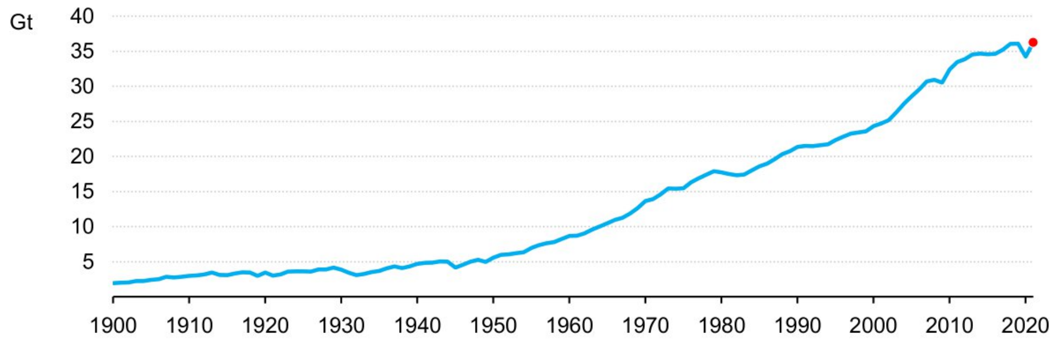

Figure 1.12 Total CO_2 Emissions from Energy Combustion & Industrial Processes 1900-2021

1.9 Forms of Renewable Energies

The most popular forms of renewable energy can be classified below and shown as a classification chart in Figure-1.13

- ➔ Wind Energy
- ➔ Solar Energy
- ➔ Hydro Energy
- ➔ Geothermal Energy
- ➔ Biomass Energy
- ➔ Marine Energy

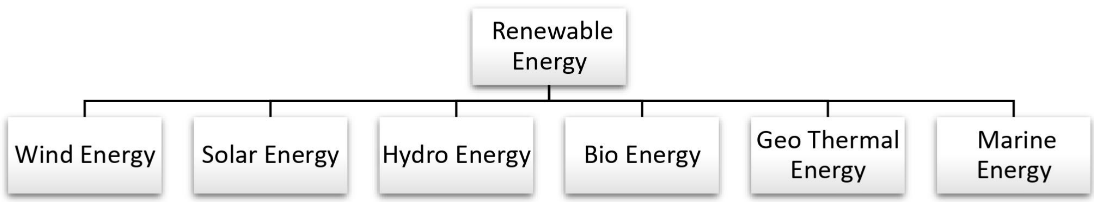

Figure 1.13 Classifications of Renewable Energies

1.10 Renewable Energy Generation Potential in India

There is a high potential in terms of energy generation from renewable energy from various sources like wind, solar, biomass, small hydro, and biogases in India. According to MNRE Survey, the total potential for renewable power generation in India as of 31.03.2022 is nearly about 14, 90,727 MW [9]. Figure-1.14 shows that The solar power potential of 7, 48,990 MW is almost 50.24%, the wind power potential of 6, 95,509 MW is almost 46.66%, the small-hydro power potential of 21,134 MW is almost 1.42%, biomass power of 17,538 MW nearly about 1.18%.Figure-1.15 shows the geographic distribution of the estimated potential of renewable power as of 31.03.2022 which indicates that Rajasthan has the highest share of about 18.2% followed by Gujarat with 12.1% & Maharashtra, Karnataka with 11.2% and 10.3% shares respectively. These four states are having more than 50% of the total potential of Renewable Power in India [9].

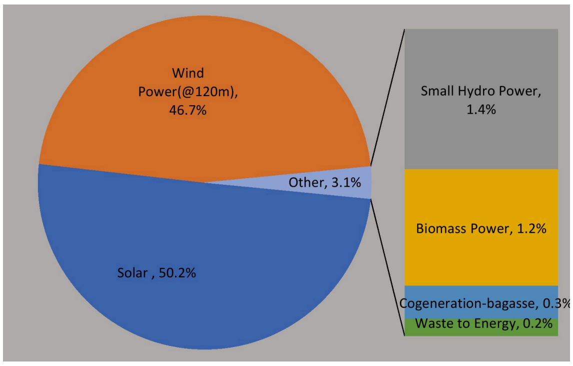

Figure 1.14 Source-wise Potential of Renewable Energy in India

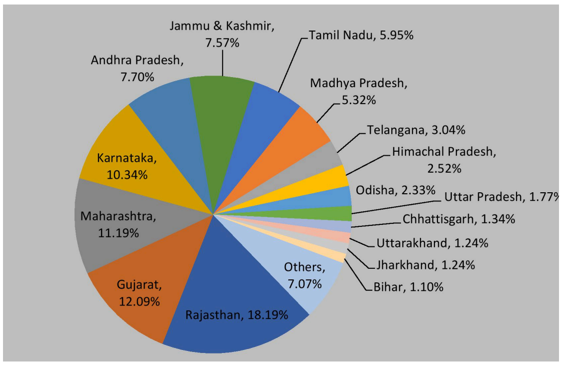

Figure 1.15 State-wise Potential of Renewable Energy in India

1.11 Advantages of Solar Energy over Other Renewable Energies

➔ The initial power production cost of wind is less expensive compared to solar, but the maintenance cost of a wind turbine is very high compared to a PV module. Moreover, wind plants need to be set up away from the locality as they make lots of noise compared to a solar PV Plant.

- ➔ Geothermal sources are limited to a few locations and there is no continuous supply of biomass. Other than that due to the combustion of biomass many volatile organic compounds such as carbon monoxide and nitrogen oxides are created. On the other hand, solar PV is a cleaner and non-toxic energy source. The energy conversion efficiency of biomass is also lower than solar. biomass plants also require a lot of space compared to a solar PV power plant.

- ➔ Solar and geothermal resources both can be used to generate clean, renewable electricity. However, for most residential and commercial sectors geothermal energy can only be used as a heating and cooling solution, while solar energy can generate electricity with photovoltaic technology.

- ➔ Hydropower plants often change the natural flow path of water resources which creates new lakes and reduces water flow downstream. Installations of hydropower plants can also affect wildlife and the existing ecosystem by blocking fish migration and altering habitats. On the other side, photovoltaic is eco-friendlier and versatile compared to hydropower.

1.12 Solar Energy Generation Potential in India

Solar energy is one of the most promising renewable energy resources among all other non-conventional energy sources. India receives a significant amount of solar radiation, which is about 300 clear sunny days [10] in a year, India receives approximately 5000 kWh/year and the daily average solar radiation incident over India varies from 4 kWh/day to 7 kWh/day. As per the national Solar Mission on 31.12.2021, a cumulative capacity of 48.087 GW of solar power projects has been installed in the country. It is expected that the target capacity of 100 GW could be fully achieved by the end of 2022 and the solar power projects of capacity around 55 GW will be commissioned by March 2022. Based on the above data the potential solar power in the country is around 750 GWp [9]. Figure-1.16 shows the state-wise details of estimated solar energy potential in the country and Figure-1.17 shows the state-wise cumulative installed capacity as of 31.12.2021 in India [9].

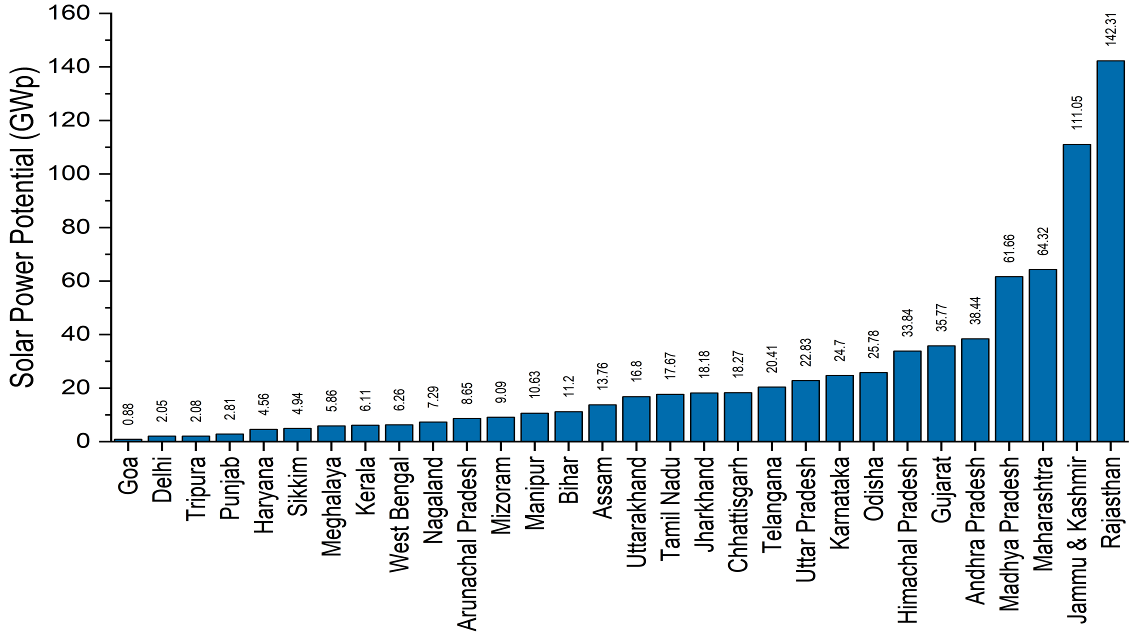

Figure 1.16 State wise Solar Power Generation Potential as on 31-12-2021

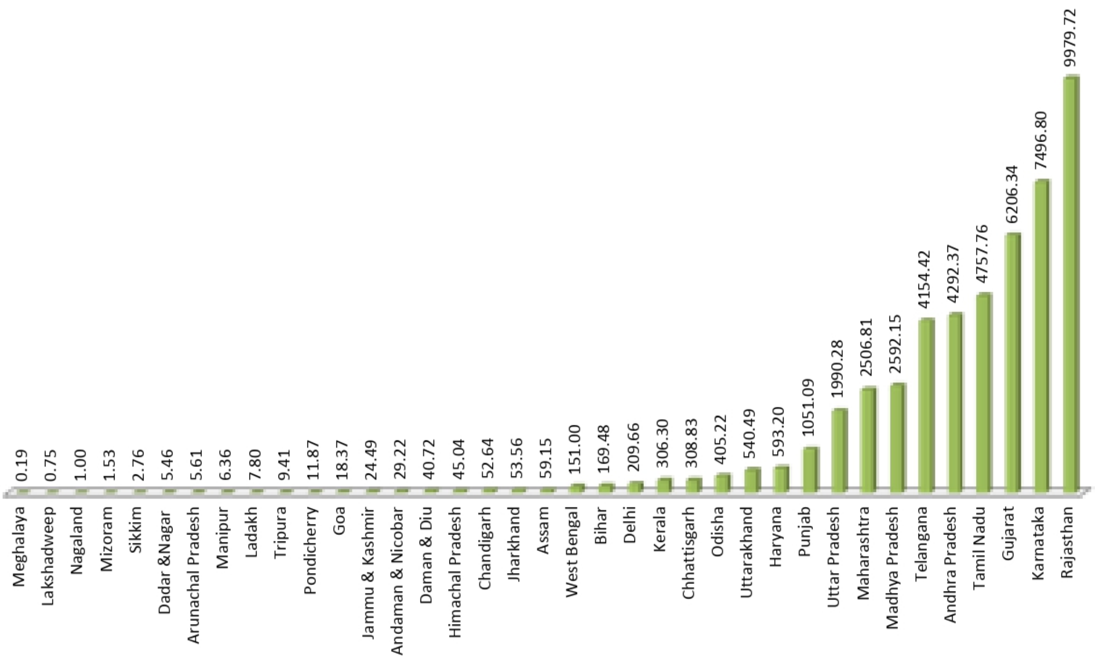

Figure 1.17 state wise Cumulative Installed Solar Power Plant as on 31-12-2021

1.13 The Objective of the Study

India is the seventh largest country in the world, being such a large country there is geographical diversity in the Indian subcontinent. The climatic condition is very different in one state compared to the other. We know that the ambient temperature, wind speed, relative humidity, and other environmental conditions such as air quality, dust particles, etc. have a huge impact on the solar module's efficiency. So for the Indian subcontinent, the power production from a solar module will be different from one state to another, not only that the power production is also heavily dependent on the PV module materials. Hence the focus of the present work is to study the effect of different environmental parameters on different solar PV module technology and try to find out the most suitable PV module for installing a solar power plant in different climatic regions of India. To execute the study the performances of m-Si and p-Si PV module with increasing cell temperature is observed by using a low-cost solar simulator in lab condition. Then the Indian subcontinent is classified into 9 climatic zones and in each climatic zone a city is chosen, hence by using the latest meteorological data, soiling loss, and degradation loss corresponding to the chosen city a techno-economic evaluation is performed using PVsyst software. In the next chapter, a brief explanation of the methodology of the study is given. Such a study will enhance the quality of prediction of the performance of solar modules under different climatic conditions and play a key role in selecting the proper type of solar module for a particular location to extract maximum utilization.

1.14 Conclusion

Conventional energy resources like oil, gas, and coal are very important for the improvement of the economic conditions of the country. In this chapter, the concept of energy and the classification of energy based on different criteria are defined. Other than that the world energy statistics the global reserves and consumption of primary energy are reported. At the same time, the Indian energy scenario is also presented. According to the comparison of solar energy with other renewable energy sources, we have established that solar energy is the most cost-efficient, eco-friendly & clean energy source compared to other renewable energy resources. Then the statistics of the generation potential and installed solar plant are shown and the objective of the present work is summarized. So, from this chapter, we can conclude that there is huge potential in the solar energy sector. That is why the work is carried out in a solar PV module. In the next chapter, the review of earlier work and the identification of the problem will give an elaborate view of the work.

Chapter-2

Literature Review

2.1 Introduction

Solar Energy has been acknowledged as a free and infinite source of energy and provides alternative energy where there is no pollution of the environment and its use will decrease the rate of depletion of energy reserves [11]. Solar photovoltaic (PV) is the fastest-growing renewable energy technology in terms of deployment capacity throughout the world. Despite being the most expensive renewable energy technology, photovoltaic technology is the easiest energy technology concerning design and installation, other than that it is a modular technology means it can be assembled anywhere required. In case of an increment in Energy requirements, new photovoltaic modules can be easily installed or added to the system within a very short time. Since there are different PV technologies a reliable long-term evaluation of these technologies under actual operation conditions would be very helpful and valuable for further development and deployment of this technology. Before investing in installing a solar power plant for a specified location, a techno-economic analysis is performed by using several meteorological data for the feasibility of the Power Plant. Through this chapter, the published work by different researcher are reviewed and the gap of knowledge is identified, later a proposed solution has been presented.

2.2 Review of Earlier Works

A.J. Carr et al. [12] showed a comparison of the performance of different PV module types in temperate climates. In this paper, the performances of five different types of photovoltaic modules such as c-Si, LGBC c-Si, p-Si, triple junction a-Si, and CIS were measured for more than a year in the temperature climate of Perth, Western Australia. Using a purpose-built outdoor monitoring system the energy production, I–V characteristics, and maximum power were measured for each module. These values are compared to the manufacturer's values and monitored over time for the modules operated in outdoor testing conditions. The conclusion that can be drawn from this paper is that if all the modules are stable and had Wp values equal to their ratings, the thin film modules would generate the most energy at this particular location. The a-Si modules produce over 15% more energy than (c-Si) in summer and around 8% more in the winter season. The CIS module consistently produces between 9% -13% more energy than (c-Si).

A comparative performance analysis of m-Si and mc-Si PV Cells executed by M. R. Abdelkader et al. [13] in Jordan**.** It investigates the performance of two photovoltaic modules at different times of the year. The measured parameters are output open circuit voltage (V_{OC}) and short circuit current (I_{SC}), Ambient temperature, and solar intensity. The performance value of the PV solar module is identified and compared with other Existing PV models. According to the article, findings indicate that the efficiency of mono-crystalline is higher than that of the multi-crystalline PV panels in the semi-arid climatic Condition of Jordan.

The performance comparison of three different types of solar panels using solar tracking devices in Malaysian climate conditions was executed by Azhar Ghazali et al. [14]. The purpose of the above study is to compare the efficiency of p-Si, m-Si, and a-Si modules in the humid climatic zone of Malaysian. It was found that p-Si solar cells performed better compared to amorphous and m-Si. Meanwhile, for low-intensity solar radiation, the efficiency of amorphous solar cells is higher than the p-Si, and m-Si Panels. The performance ratio for each type of PV module shows that p-Si is the most suitable photovoltaic module to be used in Malaysian climatic conditions.

A. Hossam El-din et al. [15] executed a comparative analysis between the performances of m-Si, p-Si, and Thin Film in Different Temperatures in Egypt. The above study investigated the effects of ambient temperature on the performance of photovoltaic (PV) panels under real conditions in the humid harsh climate of Egypt. The model investigated the characteristics and performances of the m-Si and p-Si solar panels using PSIM simulation. The study concluded that for a location having an average ambient temperature of 30° C or less the m-Si would be the best choice, while for an average temperature of 40° C or less, the p-Si would be better. The thin film would be most suitable for ambient temperatures more than 40° C.

Mustafa E.Başoğlu et al. [16] experimented with performance analysis of different photovoltaic module technologies under Turkish climatic conditions. This paper shows a comparative energy performance analysis of three different types of photovoltaic (PV) modules in Northwest Turkey. To determine the energy performances of the PV module's performance ratios, mean array efficiencies and capacity factors were calculated. The results indicate that Changes in Performance Ratios of m-Si and p-Si are lower than CdTe in the measurement period. The mean values of PR for m-Si are 83.8% for p-Si 82.05% and CdTe 89.76%. Since the CdTe has the highest CF during all months, so this will be the most suitable PV module for these climatic conditions.

D. B. Magare et al. [17] researched the effect of spectral variations on the performance of three types of PV modules in the Indian subcontinent. In this paper, the impact of seasonal spectral variations on a-Si, HIT, and mc-Si is presented. Among all three modules, HIT technology showed the least variation while a-Si showed maximum variation. The observed spectral variations affect the Performance Ratio and are compared with the reported results of other sources. This study is important in the Indian Climatic zones because of the strong monsoon season, where spectral variations are highest among all the seasons.

Aygegül tagçjollu al. [18] Experimented on a power case study for m-Si and p-Si solar panels in Turkey. The objective of the paper is to reveal the time-dependent power generation under different loads for two different types of PV module technologies in Bursa City. The efficiency of m-Si and p-Si solar modules was calculated according to the meteorological data. Within the time measurement period of the above study, they concluded that the operation of m-Si solar panels is more efficient compared to the p-Si solar panel for climatic conditions of Bursa.

Md Faysal Nayan et al. [19] researched the effect of environmental parameters on PV module efficiency for different PV modules. This paper gives a comparative study on m-Si, p-Si, and a-Si PV modules by using the model parameters. Moreover, it also illustrates the variations in fill factor and efficiency under real operating conditions. The model used in this paper is based on the fundamental circuit equations of a solar PV cell. From the analysis, it can be concluded that the performance of solar Modules depends on the standard conditions of the solar cell. But m-Si solar cell shows better efficiency than other PV modules.

The comparative performance analysis of various PV module technologies in Peru presented by Irene Romero-Fiances et al. [20] In this paper the results of a 3.3-kwp m-Si in Arequipa, a 3.3-kwp m-Si in Tacna, and a 3-kwp p-Si in Lima were compared. The outcome of the study showed m-Si and p-Si PV modules can be efficiently used in desert climates, However, the impact of high temperature and low irradiance losses on the performance of m-Si, and p-Si PV modules discourages their use in Lima due to humid coastal desert climate.

Abubakar Ohinoyi Musa et al. [21] present a comparative study on m-Si and p-Si module technologies under the Climatic conditions of Nigeria. The I-V characteristics of the two modules were measured at regular intervals. The daily, monthly, and total energy generated, efficiencies, and performance ratios throughout the test period were calculated. The findings of this study showed that m-Si is the best choice in terms of Total production of energy, efficiency, and performance ratio for this climatic region.

Fitria Hidayanti et al. [22] researched the effect of m-Si and p-Si solar cell performance in terms of conversion efficiency in Indonesia. Since in Indonesia, the dry season is longer than the rainy season so, the solar cells gain maximum intensity. The results showed that m-Si solar cells achieved an efficiency of 9.22% whereas for p-Si the achieved efficiency is 7.94%. The performance ratio for m-Si and p-Si is 83% and 80% respectively.

Experimental comparison between three different types of PV technologies m-Si, p-Si, and Thin-film solar systems in sunny climatic regions Executed by Ayadi et al**.** [23]. The study presents the performance indicators for six years of operation for five different types of solar systems, the key performance indicators are PR and efficiency. The result showed that the highest efficiency was achieved by Mono, and the lowest efficiency was achieved by the thin film. They concluded that for sunny climatic regions with moderate temperatures, p-Si showed lower performance than m-Si. In contrast, thin film systems have shown slightly better performance in terms of installed capacity than m-Si Thus, thin film PV panels can be a perfect candidate for warmer climates and dusty regions.

Noor Jamel Kadia et al. [24] experimented with the performance of two types of PV modules one is a-Si and the other is CIGS in Iraqi Climatic Conditions. The experimental work covered eight commercially available PV technologies. For the total period of 7 months, from the extracted data the analysis showed that the highest efficiency for the CIGS solar module is 7.3 %, whereas the s-Si solar module has the lowest one 5.5%.

Luis Fernando Mulcué-Nieto et al. [25] showed the energy performance of two solar systems installed in Colombia. One system was an on-grid p-Si, and another one was on-grid m-Si. The PR values obtained for p-Si was 86%, and for m-Si was 78%. This concluded that the p-Si had an optimal performance than m-si. The main cause for the optimal performance is the ambient temperature of the city which stays always under 25 ◦C.

Mabrouk Adouane et al. [26] showed a performance comparison & analysis of eight photovoltaic (PV) technologies in the harsh climatic conditions in Kuwait. The test was carried out for 8 different technologies total of 16 specimens. M-Si, p-Si, HIT, thin film, CdTe, CIGS, and a-Si. For 12 months. They concluded that The m-Si showed better performance than the p-Si, CIGS & HIT modules, Other technologies (a-Si and CdTe) performed much worse.

Michal Taraba et al. [27] executed a comparison of a-Si, m-Si, p-Si, and thin film CIGS solar panels technologies for home applications. The work compares the production of electric power in adverse weather conditions. All the measurements were performed with a cloudy sky and snowfall. The result concluded that thin films are most suitable for cloudy weather whereas m-Si and p-Si panels have a higher efficiency and better performance than thin film during sunny days. Other than that when the solar panel is shaded, the thin film shows better responses.

Erdem Elibol et al. [28] tested PV modules in the laboratory at standard test conditions (STC). This study focuses on outdoor testing of three different PV panels (m-Si, p-Si, and a-Si) performances throughout the year on the roof of Düzce University Scientific and Technological Researches Application and Research Centre (DUBİT), in Turkey, Recored panel efficiency for a-Si is 4.79%, for p-Si 11.36% and m-Si is 13.26% All results compared and using a Statistical analysis the relationship between efficiency and performance ratios, ambient temperature, panel temperature and amount of radiation is determined. The study concluded that the temperature coefficient of a-Si panels is 0.029% is positive, the temperature coefficient of p-Si panels is 0.033% is negative, and the temperature coefficient of m-Si panels is 0.084% negative.

Abderrazzak Elamim et al. [29] evaluated the performance analysis and the economic analysis of a solar photovoltaic grid-connected system in Morocco. The experimental research was performed on three types of PV modules (m-Si, p-Si, and a-Si). The performance is based on output-tested parameters such as the total generated energy, performance ratio, capacity factor payback time, cost of energy, etc. Among all these PV systems installations, the p-Si showed the highest performance in terms of tested parameters compared to other Si technologies. So, it can be said that p-Si is the most suitable photovoltaic module to be used in the Moroccan climate.

The study on optimal recycling process with a high resource recovery efficiency was executed by Mitchell Shyan Wei Lim et al. [30]. The study explores module delamination, acid etching, and sequential electrode position. The industrial process and its human and environmental impacts were compared with six impact categories such as global warming, human toxicity, freshwater Ecotoxicity, acidification, eutrophication, and ozone depletion. Lastly, the economic analysis showed that the process is feasible with an internal revenue rate of 28.2% and a payback time of less than a year, with the condition of subsidized waste collection.

A comparative Analysis of m-Si and p-Si PV module power generation in a Semi-Arid climatic region in Iran executed by Mohsen Mirzaei et al. [31] as expected, the power output of both modules increases with the irradiance. The monthly average efficiency for an m-Si module lies between 15.2% to 13.2%, whereas for p-Si modules the efficiency lies between 12.97% to 11.44%. The result indicates that for the m-Si module, the efficiency has a gradually decreasing trend with higher solar irradiance and temperature, while the p-Si module shows inverse behavior. Finally, they concluded that under the semi-arid climatic region of Iran, the p-Si module is more suitable in the summer months, while the m-Si module is more efficient in the non-summer months.

Mohamed Louzaznia et al. [32] executed a comparison of power production for three Different Photovoltaic Technologies in Egypt, the study is carried out over three different months in 2015, and during the study, the solar radiation and ambient temperature were measured. The solar irradiation and temperature of each module were compared for April, August, and December, and the maximum power point (MPP) was compared in August.

The above study concluded the p-Si module gives better performance for April, August, and December compared to m-Si and Thin Film modules.

The global distribution of climate stressors affecting photovoltaic degradation was analyzed by Todd Karin et al. [33]. From all the previous research it can be concluded that the climatic parameters affect photovoltaic (PV) degradation in terms of power loss and system failures. Typically the Köppen-Geiger classification scheme is used to compare Solar PV module degradation across the different climatic zone. The study concluded that The photovoltaic Climate Zones (PVCZ) scheme gives a detailed understanding of which types of degradation may be expected in different geographic areas.

Talat Ozden et al. [34] executed a countrywide analysis of 27 solar power plants installed in different climatic zone in Turkey. Before investing in a solar power plant in a specified location, a techno-economic analysis is performed by using several meteorological data. However, in this work, the data from 27 grid-connected photovoltaic power plants installed at seven different climatic zones in Turkey over 5 years is collected and investigated. The outcome of the techno-economic results indicates that power plants should be carefully treated.

Satish Kumar Yadav et al. [35] showed a variation in solar photovoltaic power plants due to climatic parameters in a composite climatic zone. In this paper, the effect of soiling on the performance of solar power plants was measured for April 2016. As April gets more sunlight compared to other months so it is the dirtiest month. The wind speed is highest in April (10 kmph). Due to High wind speed, Aeolian dust precipitates on the module and the efficiency was reduced up to 11.4% in April. As an outcome of the study, A correlation model has been established between the effects of different climatic parameters and the reduction in module efficiency.

A performance modeling of the weather impact on PV Power Plant in a Tropical Region by Ajith Gopi, et al. [36]. The present work indicates the influence of important weather parameters on the performance of power plants installed in the state of Kerala, India. Here big data is collected from the Solar Radiation Resource Assessment for accurate estimation. Other than that the ambient temperature, global tilted irradiance, wind speed, rain, atmospheric pressure, and humidity are also analyzed and modeled for this region. The study concluded that the 2mwp PV plant has higher PR in rainy seasons due to the colder temperature during rainy seasons. Future work on this paper can be done on performance analysis of PV plants in some other geographical regions in India or outside India with different climatic conditions.

In their review, Maxime Mussard et al. [37] emphasize the installed PV technology in arid and semi-arid climatic regions. The objective of this paper is to determine the recent uses of solar PV modules in arid climatic regions with the evolution of PV technologies. The novelty of this work is to present up-to-date experimental results for one year or more under such climates and to plot the experimental result considering the effect of environmental parameters on different locations and technologies. The impact of these parameters on the PV module's performance and degradation is important for installing a power plant in such climatic regions. From this review, it can be concluded that Arid and semi-arid climates offer enormous amounts of solar irradiance however a careful assessment of the environmental parameters is necessary before selecting an appropriate solar PV technology for arid and semi-arid climatic conditions.

Suprava Chakraborty et al. [38] worked on a mathematical method to determine the best PV module technology for different climatic zones of India This paper presents a reliable mathematical method to predict the energy generation from the grid-connected photovoltaic plant of different commercially used technologies in different zones of India. Depending on GHI and ambient temperature India is classified into 15 climatic zones. Using the proposed mathematical model the Energy generation for different types of PV technologies in 15 different climatic zones in India is predicted. The study gives a proper way for installing the most suitable PV technology for different climatic zones of India.

Economic analysis of 26 kW solar PV system for a commercial building in India executed by Mohammad Suhail et al. [39] A 26 kW grid-connected solar PV system is installed in New Delhi, India The aim of this study is the economic analysis of a 26 kW solar PV system and techno-economic comparison between the grid-connected and a standalone system. The result of the study shows that a grid-connected system is 32% more economical than a standalone system.

A techno-economic analysis of photovoltaic systems performance in Iran done by Hamed Yazdani et al. [40]. In the economic analysis research averages of soiling loss and yearly degradation of PV modules were obtained according to the measured data hence for the 1 MW solar plant modeled in pvsyst software as per the measured data for 3 years. The economic assessment indicates that investment in the PV industry without any government support is economically profitable, where the payback period is 5.82 years. Based on the experimental data as well as the simulation, an economic analysis suggested a cost-benefit construction for a 1MW solar PV power plant in this region.

.Mevin Chandel et al. [41] a techno-economic analysis on a solar PV power plant in Jaipur city. In this paper, the potential of generation and the cost-effective solution for the solar PV plant is analyzed. At the same time, an off-site proposal for the power plant has also been considered and compared with the on-site PV plant. The result indicates that for the onsite plant, the payback period is 7.73 years, and with a discount, the payback period is 15.53 years whereas for the off-site power plant, the payback period is 6.29 years and the discounted payback period is 10.14 years.

A systemical design and cost analysis for a 1 kwp PV system based on performance in the Indian subcontinent region is executed by Shahzad Ahsan et al. [42]. The study calculates both monthly and weekly costs of production of energy for a 1 kwp PV system. This paper, presented for designing a system for small homes where the grid power is hard to reach. It is very useful in rural areas of the Indian subcontinent.

Techno-economical analysis of a 3-kwp PV system in Nepal executed by Ramhari Poudyal et al. [43]. The study analyses the importance of the technical feasibility of designing a PV system using pvsyst and Meteonorm software. The key output performance indicators are energy output, performance ratio, and the return period. The key input parameters are site-location-specific meteorological data, solar irradiation, PV capacity factor, and the tariff rate of electricity. According to the result, the solar PV system can save 10.33 tons of CO_2 emissions over its lifetime. Overall, the 3 kwp PV systems can be considered a feasible solution to generate a sufficient amount of electricity.

Nallapaneni Manoj Kumar et al. [44] worked on a performance analysis of a 100 kwp grid-connected p-Si PV system using pvsyst software. The study was conducted to evaluate the feasibility of installing a PV system. The simulated system was designed using 323 Wp p-Si PV modules. Due to the change in climatic conditions throughout the year the generation may vary. From the results, it can be concluded that the planned proposed PV system will provide operational benefits.

A Comparison of produced power for different PV technologies in climatic conditions of Egypt executed by Mohamed Louzaznia et al. [45]. During The study, the solar radiation and the ambient temperature were measured for three months in the year 2015. The paper concluded that the difference in voltage of the inverter and power output for p-Si PV modules is larger for the selected three months compared to m-Si and Thin Film PV modules.

2.3 Gap of Knowledge

From the above literature review, we can understand that there are lots of studies that have been performed regarding the comparison of m-Si & p-Si Solar cells in different climatic zones all over the world but there is no such study on Indian climatic conditions. As we know due to the geographical location of India there are several climatic zones in India so the soiling loss and degradation loss will be different for the different climatic zone in India. Moreover, there is no economic analysis according to the tariff rate and benchmark cost approved by the government of the respective state or as per MNRE regulation. Since there are different PV technologies available in the market so for a reliable long-term evaluation of these technologies under actual operation conditions would be very helpful and valuable for further development and deployment of this technology. Before investing or installing a solar power plant in a specified location, an economic analysis is required to check the economic feasibility of the Power Plant.

2.4 Probable Solution

As stated in the above section the problem can be solved by conducting a techno-economic analysis for each city according to the tariff rate along with the soiling loss, degradation rate, and benchmark cost as per government rule. From the obtained result we can be able to predict the type of PV module that can be installed in that particular location and extract maximum utilization. Such a study will enhance the performance of solar modules under different climatic conditions and play a vital role in selecting the proper type of solar module for a particular location for a specific application.

2.5 Scope of the Present Work

So far in the reviews section, All the previous work related to the comparative performance analysis of various types of solar modules such as m-Si, p-Si, thin film, etc. based on different parameters for different climatic regions all over the world are reviewed, and analyzed, other than that the techno-economic analysis for installing a solar PV power plant for a specific location are also reviewed. In this study, the work based on the proposed solution is executed through the following steps.

- ➔ The I-V characteristic data of both m-Si and p-Si solar modules along with temperature have been recorded in the lab setup condition.
- ➔ The efficiency of both panels with temperature is plotted and a conclusion is drawn regarding the better efficiency between these two.
- ➔ Hence 9 climatic region is identified in India as per the latest data, for each climatic zone one city is chosen.
- ➔ For each city, according to NSRDB data, the last 3 years meteorological data is taken.
- ➔ Now in PVsyst software by importing the latest meteorological data for each city a techno-economic analysis is presented along with a range of soiling loss, degradation rates, tariff rates, and benchmark Costs as per government rule.
- ➔ Hence from the data set a graphical view is presented for output parameters such as production cost of energy, ROI, Saved Carbon Emission, and payback period for both m-Si and p-Si for different cities.
- ➔ Hence it can be concluded that for which climatic zone which type of module is most suitable.

The whole work is presented in the form of thesis .Where the basic introduction of energy, utilization & its importance of renewable energy (solar energy) are discussed and the preliminary objective of the present work are elaborated. Whereas in the present chapter the detailed review work is carried out to find the gap of the knowledge as well as possible solutions. The overview of the present work is also described. In Chapter-3 a basic overview of solar PV technology is presented how they work and the characteristic of the solar cell, types of PV modules, etc. In Chapter-4 a basic overview of PVsyst software is given. Chapter-5 gives a brief explanation of the experimental setup such as the data measurement process, circuit, etc. whereas in Chapter-6 the result of the study has been discussed.Chapter-7 concluded the study and gives a view of the future scope of the work study has been discussed.Chapter-7 concluded the study and gives a view of the future scopes of the work.

2.6 Conclusion

In this chapter, a review of previous work is presented. From the reviewed section the actual problem is identified and a probable solution is proposed. Next, the objective of the present work and the step through which the proposed work is implemented is summarized. The next chapter will give us a proper overview of Solar Cells including how they work and their characteristics.

Chapter-3
Solar PV Technology

3.1 Introduction

In Chapter-1 we already discussed why solar energy is considered as the most demanding renewable energy than other renewable energy resources. Solar PV technology is an appropriate and cost-effective source of electricity for many applications in developing regions of the world. PV systems bring people basic services and amenities, such as light, water, communications, power for businesses, and power for other productive uses in an environmentally sensitive manner. PV systems are especially well suited for use in rural areas where large populations remain isolated from existing power distribution networks, it may also be the most cost-effective means of supplying basic services when their life-cycle costs are compared against typical alternatives, such as the use of kerosene and candles for lighting, or the expansion of existing power distribution networks. The high reliability of PV systems also makes them suitable for use in urban areas that may already have some access to a centralized electric power source and distribution grid. In this chapter, we will discuss the concept of solar cells, how they work, and modern solar PV technologies.

3.2 What is Solar Cell

A photovoltaic cell or Solar cell is a semiconductor device that converts light energy directly into electric energy through the photovoltaic effect. It is a photoelectric cell, whose electrical characteristics, such as current, voltage, or resistance, vary when exposed to light. Individual solar cell devices can be combined to form modules and arrays, which are commercially known as solar panels.

3.3 History of Solar Cell

“Photovoltaic” is the term derived from the Greek word for light - photos- and the name for the unit of electromotive force-volt. Photovoltaic means the direct generation of electricity from light. This process is utilized through solar cells [46].

- ➔ In 1839 Edmund Becquerel, a French physicist first observed the photovoltaic effect.
- ➔ In 1883 Selenium PV cells were built by Charles Edgar Fritts, Cells converted light in the visible spectrum into electricity with an efficiency of 1% to 2%
- ➔ In the early 1950's the Czochralski meter was developed for producing highly pure crystalline silicon.
- ➔ In 1954 Bell Telephone Laboratories produced a silicon PV cell with a 4% efficiency and later achieved 11% efficiency.
- ➔ In 1958 the US Vanguard space satellite used a small (less than one watt) array to power its radio. The space program has played an important role in the development of PVs ever since.
- ➔ During the 1973-74 oil price shock several countries launched photovoltaic utilization programs, resulting in the installation and testing of over 3,100 PV systems in the USA alone, many of which are in operation today.

3.4 Basic Theory of Photovoltaic Effect

The photovoltaic effect is a process that generates electricity by using a photovoltaic cell when it's exposed to the sun. These solar cells consist of two different types of semiconductors a p-type and an n-type which are joined together to create a p-n junction. After joining these two types of semiconductors, an electric field is generated in the region of the junction since electrons move to the p-side whereas holes move to the n-side. Due to the formed electric field negatively charged particles move in one direction and positively charged particles in the other direction. Since light is an electromagnetic wave it is composed of photons, which are small bundles of electromagnetic energy. These photons can are absorbed by a photovoltaic cell based on the band gap energy of the material. When the light of a desired wavelength is incident on these cells, energy from the photon is transferred to an atom of the semiconducting material in the p-n junction.

3.5 How Solar Cell works

Once the photons absorb the energy then the electrons jump to a higher energy state from the existing energy state which is known as the conduction band. With this process, the electron leaves behind a "hole" in the valence band. Due to this phenomenon, an electron-hole pair was created. When unexcited, electrons hold the semiconducting material together by forming bonds with surrounding atoms, and thus they cannot move. However, in their excited state in the conduction band, these electrons are free to move through the material. Because of the existing electric field in the p-n junction, electrons, and holes move in the opposite direction as expected. Instead of being attracted to the p-side, the free electron tends to move to the n-side. This motion of the electron creates an electric current in the cell. Once the electron moves, there's a "hole" that is left. This hole can also move, but in the opposite direction to the p-side. It is the process that creates current in the cell [47]. Figure-3.1 shows the working principle of a solar cell.

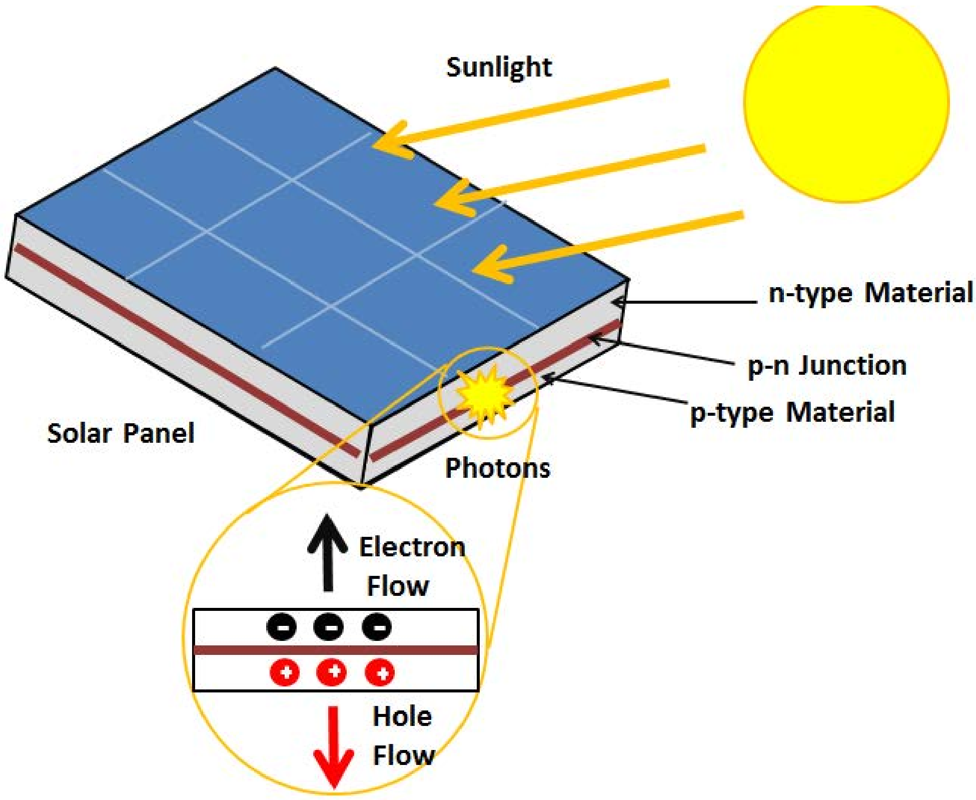

Figure 3.1 Concept of Solar Cell

3.6 Six Main Components of a Solar Panel

3.6.1 Solar PV Cells

Solar PV cells convert sunlight directly into DC electrical energy. The performance of the solar panel depends on the cell type and characteristics of the silicon used. A very thin wafer, typically 0.1 mm thick is the base of the PV cell which is made from either positive p-type silicon or negative n-type silicon [48].

3.6.2 Glass

To protect the PV cells from the natural impact of hail or airborne debris the glass is used, the glass is typically high-strength tempered glass which is 3.0 to 4.0mm thick and is designed to resist mechanical loads and extreme temperature changes.

3.6.3 Aluminum Frame

For protecting the edge of the laminate section of the cells a solid structure to mount the solar panel in the position of an aluminum frame is stationed. These are designed to be lightweight and able to survive against wind and other external forces.

3.6.4 EVA Film

A specially designed polymer, a highly transparent layer used to encapsulate the cells and hold the position. EVA is referred to as 'ethylene vinyl acetate'. Prevention of moisture and dirtiness are the main two obstacles to the long-term performance of PV modules that are encountered by The EVA.

3.6.5 Back sheet

The moisture barrier and final external skin provide both mechanical protection and electrical insulation the back sheet is used. This is the last layer of solar panels. The back sheet material is generally made of polymers including PVF, PP, and PET. It also gives thermal stability and protection from long-term UV resistance.

3.6.6 Junction Box

The junction box securely attaches the cables required to interconnect the panels. It also includes the bypass diodes which prevent back current which occurs when cells are shaded or dirty. Diodes are unidirectional, bypassing the diode for preventing reverse currents.

Figure-3.2 represents the cross-sectional view of a solar module

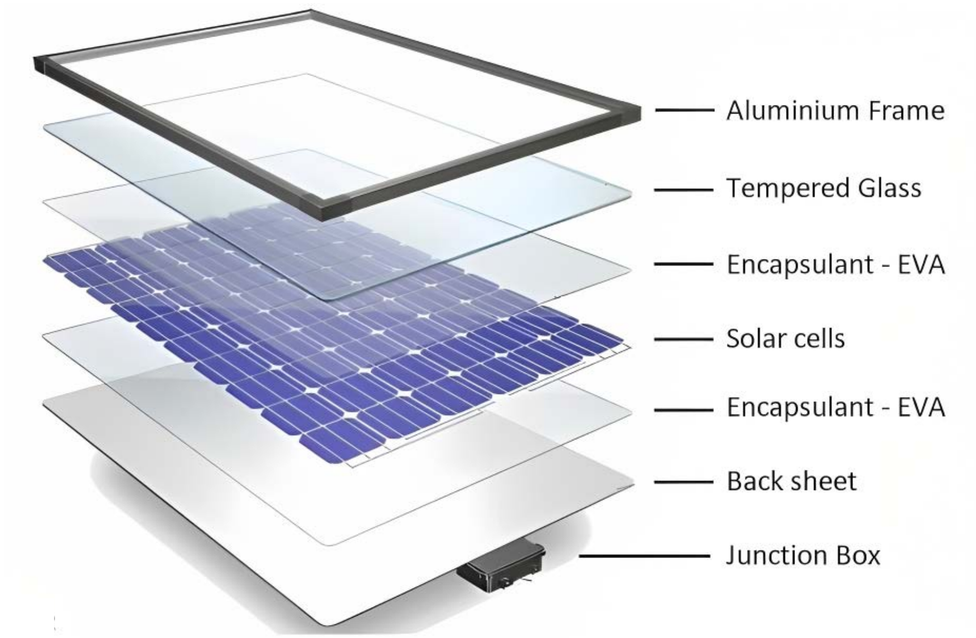

Figure 3.2 Component of Solar Module

3.7 Characteristics of Solar Cell

3.7.1 I-V Curve

Figure-3.3 shows the I-V Characteristics of a diode. The blue color shows the voltage and current of a diode. The red color for a solar cell. The sum of these two currents represents the total current (I_L), due to the illumination. For the study of photovoltaic cells, it is usual to change the polarity references, considering I_L as a positive quantity (instead of negative as it appears in the figure). Taking the generation currents as positive, we can write

$$I = I_L - I_D \qquad (1)$$

Which is the characteristic equation of the solar cell. According to the equivalent circuit of a solar cell, the mathematical equation can be expressed through the model of a single exponential,

$$I = I_L - I_0 \left[\exp \frac{eV}{mkT} - 1 \right] \qquad (2)$$

Where e is the charge of the electron, and k is the Boltzmann constant. Figure-3.4 shows the I-V Characteristics of a solar cell [49].

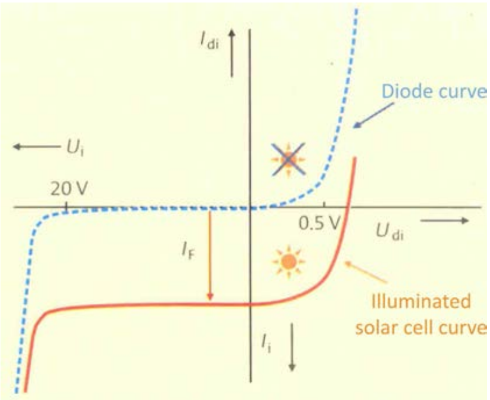

Figure 3.3 I-V curves of a diode and an illuminated photovoltaic Cell

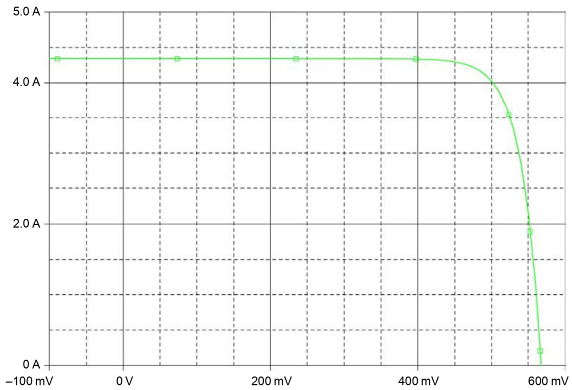

Figure 3.4 I-V curves of a Solar Cell

3.7.2 Short-Circuit Current & Open-Circuit Voltage

According to the previous equation, the short-circuit current I_{sc} is expressed as

$$I_{SC} = I(V = 0) = I_L \qquad (3)$$

If the device is kept in an open circuit, the voltage will be maximum, it can withstand in the generation region. It is about the open circuit voltage, denoted as V_{oc} and its value is such that the photocurrent is completely compensated by the polarization current. This is, I_L, is open-circuit conditions and, taking into account Eq. (2) that defines

$$V_{OC} = m \frac{kT}{e} \ln \left(\frac{I_L}{I_0} + 1 \right) \qquad (4)$$

In addition, to have a model closer to reality we should include two elements that are the series resistance and the parallel resistance, which affect the efficiency of the cell. The series resistance of the cell, R_S, is an internal resistance due to factors such as the resistance of the semiconductor with which the cell is manufactured. It is commonly assumed in practice that all these resistant losses can be represented by a resistance which is called the solar cell's series resistance (Figure-3.5). The parallel resistance R_p appears due to imperfections in the quality of the p-n junction and is responsible for the existence of current leakage (Figure-3.6) [49]. The mathematical expression that relates current and voltage is

$$I = I_L - I_D$$

$$I = I_L - I_0\left[\exp\frac{e(V+R_sI)}{mkT} - 1\right] - \frac{V - R_sI}{R_p} \qquad (5)$$

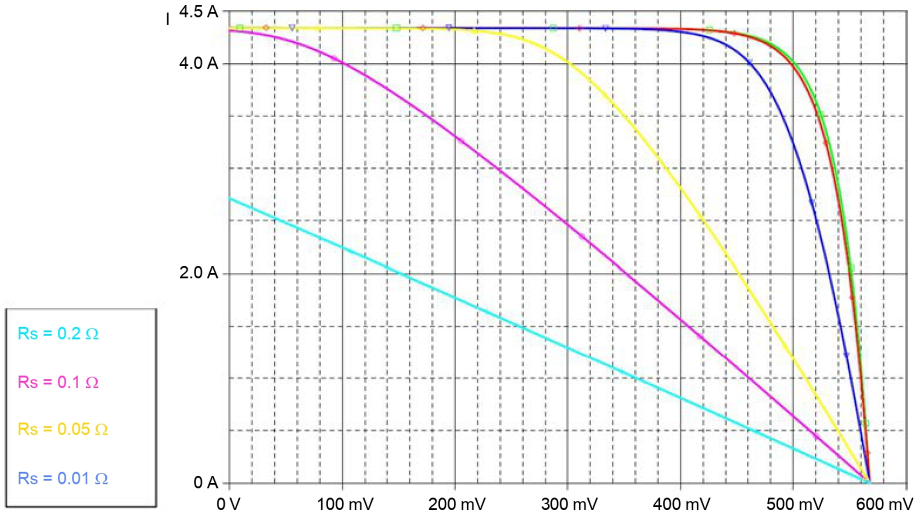

Figure 3.5 Effect of the Series Resistance on I-V Curve

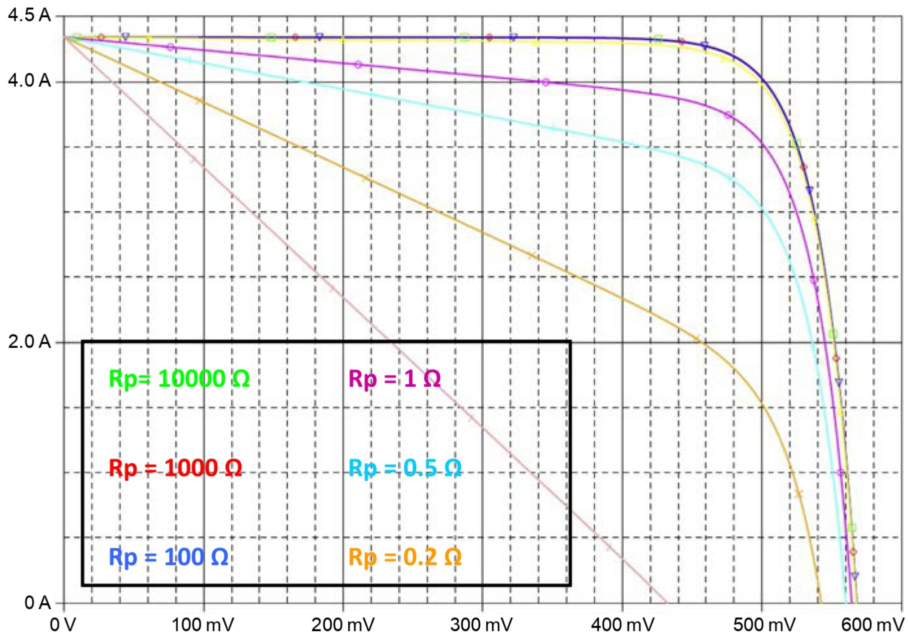

Figure 3.6 Effect of Parallel Resistance on I-V Curve

3.7.3 Power Curve & Maximum PowerPoint

For each point of the I-V curve, there is a value of voltage and working current, that is, a power, which can be represented as shown in Figure-3.7. When the cell is short-circuited, the current value of the I-V curve is the maximum, but the voltage is zero, so the power that is delivered is zero [49]. Similarly, when the cell is open-circuit the current is zero, then the voltage is maximum, as a result, the power delivered is zero. If the energy is supplied to a load with nonzero resistance, the power delivered to the resistance is given by the product of the corresponding current and voltage. There is an operating point (I_{mpp}, V_{mpp}) for which the power delivered is maximum.

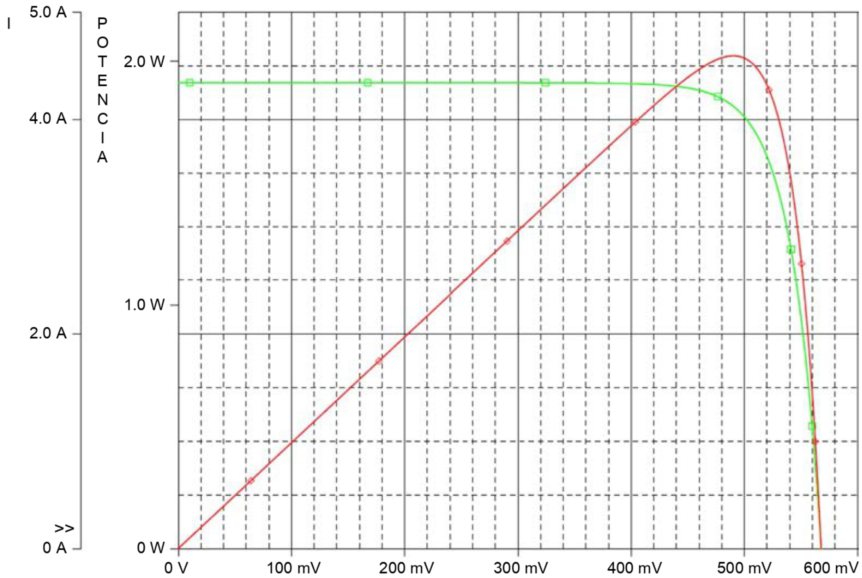

Figure 3.7 Power Curve of a Photovoltaic Cell

3.7.4 Fill Factor

The product of I_{mpp} and V_{mpp} gives the maximum power delivered to the load, which is smaller than the product of the largest current that can be extracted from the cell by the higher voltage, $(I_{SC} \times V_{OC})$. The Fill factor is defined as $FF = \frac{(I_{mpp} \times V_{mpp})}{(I_{SC} \times V_{OC})}$ always less than "1". The fill factor of crystalline semiconductor cells is around 0.7 or 0.8 [49]. Using the definition of the fill factor, the maximum power delivered by the cell can be expressed as.

$$P_{max} = FF \times V_{OC} \times I_{SC}$$

3.7.5 Cell Conversion Efficiency

The energy conversion efficiency of a solar cell is defined as the ratio between the delivered maximum electrical output power to the load with the incident radiation power of the. $\eta = \frac{P_{out}}{P_{in}} \times 100\%$ Naturally, this efficiency and the maximum power are obtained only if the load resistance is sufficient, which is given as $\frac{V_{mpp}}{I_{mpp}}$. So if we say that a commercial PV cell has an efficiency of 15%, which defined that if we consider the surface area of the PV cell is 1 m^2, so, for every 100W/m^2 of incident radiation, only 15 W power will be delivered to the load rest of the incident energy are lost due to reflection, internal resistance, recombination processes, etc. [49].

3.7.6 Influence of Temperature

As we have seen in an earlier section the short-circuit current increases slightly with increasing temperature, but there is a significant decrease in the open-circuit voltage (Figure-3.8) [49]. Now since the power is the product of voltage and current so the performance of a solar cell decreases with temperature. The photocurrent I_L increases slightly with the temperature (Figure-3.9) due to the increase in the diffusion lengths of the minorities and partly to the narrowing of the band gap, which shifts the absorption threshold toward lower energy photons. The improvement of the photocurrent with temperature is more distinct in GaAs cells than in Si cells, but overall, the variation is small and, I_L can be considered independent of temperature therefore, the operating temperature of the photovoltaic solar cells has a very significant effect on the electrical response of the module.

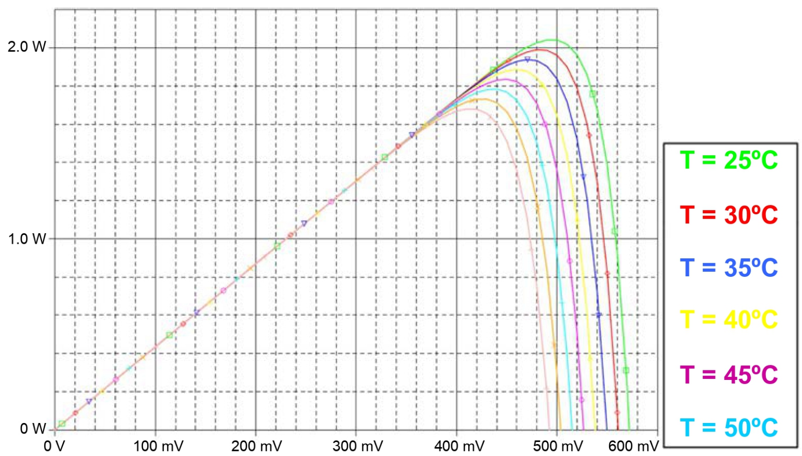

Figure 3.8 Effect of Temperature on V-I Curve of a Photovoltaic Cell

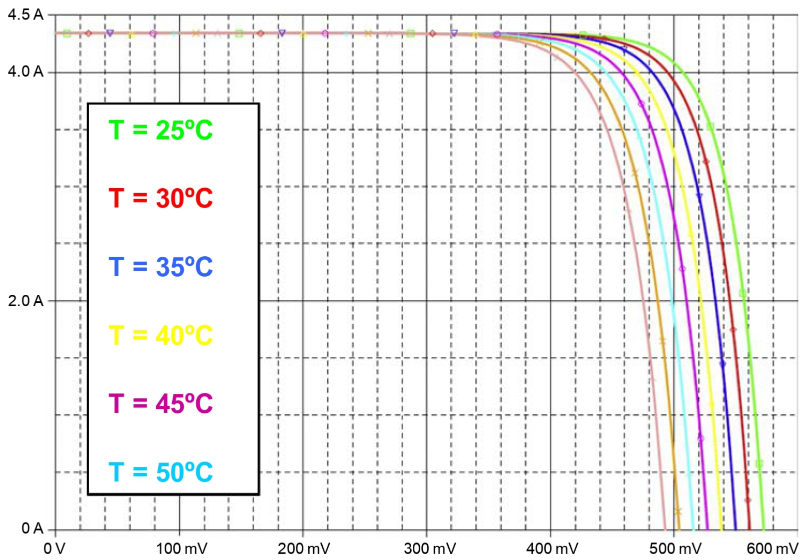

Figure 3.9 Effect of Temperature on a Photovoltaic Cell

3.7.7 Standard Test Conditions (STC)

We have seen that the current-voltage (I-V), and power-voltage (P-V) characteristics vary with solar radiation intensity ambient temperature. Now to compare two or more types of PV cell technology we need to establish standard test conditions which are referred to as (STC). By establishing a fixed set of conditions, all manufactured solar panels can be compared and rated more accurately against each other. The three conditions are stated as 1000 W/m^2 Solar radiation intensity, 25^{0}C Cell temperature and 1.5 Air mass means the amount of light passing through the Earth's atmosphere before it can hit the surface of the Earth. For AM 1.5 the spectral distribution, out of the total incoming solar radiation energy, 54% falls in the visible range, 44% in the infrared, and 2% of the energy in the ultraviolet portion [49].

3.8 Generations of Solar Cells

Over the past few decades, photovoltaics become a major contributor to meeting ongoing energy demands. However, there are still several challenges before photovoltaics can provide cleaner and low-cost energy commercially. Research is still ongoing for the development of manufacturing methods and PV cell material such as multi-junction cells, intermediate band gap cells, quantum dots solar cells, etc. Throughout the research period, we have found many manufacturing methods for fabrication of the solar cells. As per the Current scenario, the photovoltaic module technologies can be divided into four generations (Figure-3.10).Figure-3.11 represents the efficiencies of different PV cells along with their generations.

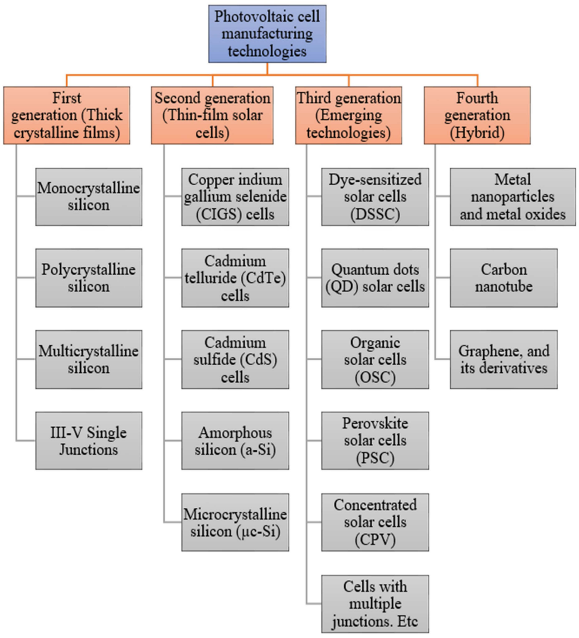

Figure 3.10 Generations of Solar cells

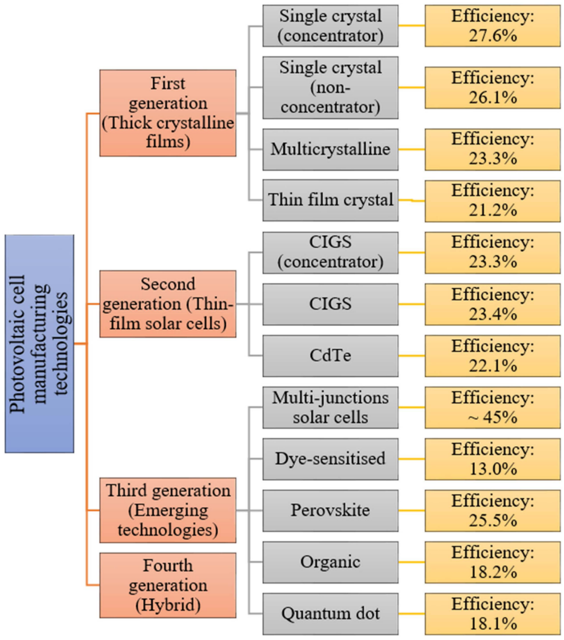

Figure 3.11 Efficiencies of various Solar Cells

3.8.1 First Generation of Photovoltaic Cells

The first commercially available photovoltaics were silicon-based PV cells. More than 90% of the global market share and nearly about 80% of the world's installed PV capacity consist of silicon-based PV modules. Due to the high efficiency of silicon-based PV modules compared to other compounds, they are the most commercially used solar cells. The first generation of photovoltaic cells includes materials based on thick crystalline layers composed of silicon. This generation is based on m-Si, p-Si, mc-Si, GaAs Cells, etc. [50].

3.8.1.1 Monocrystalline Silicon Solar Cell

m-Si silicon cells (Figure-3.12) are generally referred to as silicon cells. As the name indicates, the cell is formed from a single crystal of silicon. The manufacturing process begins by extracting the metallurgical-grade silicon from the sand in which silicon contains a huge amount of unwanted impurities. After the refining process, $SiHCl_3$ (trichlorosilane) was extracted from the metallurgical-grade silicon. This is done because $SiHCl_3$ is a liquid compound, with liquids being easier to purify than solids. After this purification process, $SiHCl_3$ of high purity is obtained. Then the solid form of silicon is recovered. Mixing $SiHCl_3$ with H_2 and heating produce polysilicon (solid) and HCl. Despite of more purified this polysilicon, still does not constitute a monocrystal. The final production of the monocrystal can be done by the Czochralski process [49]. The outcome is a circular bar of silicon. Through the cutting process, the silicon bar is produced, then the manufactured m-Si silicon solar cells wafers are extracted. The efficiency of m-Si PV modules is in the range of 15%-24%.

3.8.1.2 Polycrystalline Silicon Solar Cell

Despite being an efficient PV cell the cost of an m-Si PV cell was very high. To counter this situation the use of p-Si silicon cells (Figure-3.13) is introduced by the strategy of cost reduction by reducing the cost of wafers. p-Si silicon doesn't contain crystalline silicon grains. The same manufacturing techniques can be used for p-Si as we used previously for m-Si PV cells. Due to the additional recombination in the boundary of p-Si the efficiency of these cells is lower compared to m-Si. The degradation rate of p-Si is also lower compared to m-Si. In the manufacturing process of p-Si, there are a few technical difficulties such as texturing which heavily depend on the crystalline orientation of the material. In the laboratory, efficiencies of 16.8% have been achieved with large-area cells [49]. At the industrial & commercial levels, the efficiency is around 17%.

Figure 3.12 Monocrystalline Solar Cell

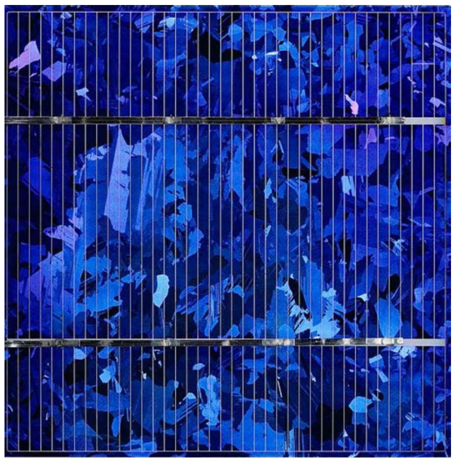

Figure 3.13 Polycrystalline Solar Cell

3.8.2 Second Generation of Photovoltaic Cells

Due to the cost of raw silicon, there is a requirement to find cheaper compounds for the production of the solar cell, which is fulfilled by the thin film photovoltaic cells, which are based on CdTe, GaSe, CIGS, a-Si, etc. These types of PV technologies offer improved mechanical properties for more flexible applications, but this comes with the risk of reduced efficiency.

3.8.2.1 Amorphous Silicon Solar Cell

A-Si lacks the ordering of silicon atoms in its crystalline lattice. In a-Si, due to the high density of defects, it prevent the material from showing minimal transport and recombination properties. a-Si (Figure-3.14) is much more absorbent, very few microns can absorb more sunlight compared to conventional crystalline material. By depositing the silicon directly on a glass or plastic substrate the a-Si cells are manufactured. Manufactured amorphous cells have an efficiency of around 10%. By alloying it with nitrogen or carbon, the value of its gap can be increased combining the a-Si with germanium alloys that would give an approximate gap of 1.45eV and with carbon or nitrogen to obtain a gap of 2.0 eV, It is noted with germanium the efficiency can reach up to 24% [49]. The main application of a-Si is in calculators and watches.

3.8.2.2 Gallium Arsenide (GaAs) Solar Cell

The GaAs is a direct gap material which indicates that it is a very absorbent material. Very few microns of GaAs material are enough to absorb all the incident light. Subsequently, on the upper part of the substrate, the photovoltaically active layers in this cell play a mechanical supporting role. Due to high resistive properties against the radiation GaAs solar cells are frequently used in space applications [49]. Due to the high cost of production of substrate glasses, the commercialization of this type of solar cell is limited. The measured efficiencies are around 21% for AM 1.5G. Figure-3.15 shows the structure of a GaAs solar cell.

Figure 3.14 Amorphous Silicon Solar Cell

Figure 3.15 Gallium Arsenide (GaAs) Solar Cell

3.8.3 Third Generation of Photovoltaic Cells

From inexpensive low-efficiency systems to expensive high-efficiency systems offered in the third generation of solar cells. The main application of this generation's solar cell is in the space shuttle. Third-generation photovoltaic cells are often termed "emerging concepts" because of their poor commercial market penetration, despite some being in the research & development phase for more than 25 years.

3.8.3.1 Dye-Sensitized Photovoltaic Cell (DSSC)

Figure-3.16 shows A schematic representation of dye-sensitized organic photovoltaic cells (DSSCs) It is a hybrid organic–inorganic structure where a highly porous, nanocrystalline layer of titanium dioxide (TiO_2) is used as a conducting material. An electrolyte solution containing optically active organic or inorganic dyes that can absorb light and initiate charge transferring process near the interfaces resulting transportation of holes in the electrolyte [50]. The power conversion efficiency is nearly about 11%, and commercialization of dye-sensitized photovoltaic modules is in progress.

3.8.3.2 Quantum Dots Photovoltaic Cell

Quantum dots solar cells are also referred to as nanocrystalline solar cells. These types of cells are fabricated by using the epitaxial growth method on a crystal substrate. Quantum dots are surrounded by high potential barriers in a 3-D shape. Since the quantum dots solar cells are confined in a small space as a result the electrons and holes become discrete energy states (Figure-3.17). As a result, the ground state energy of electrons and electron holes depends on the size of the quantum dot. Nanocrystalline cells have relatively high absorption coefficients compared to other solar cell materials. The highest recorded efficiency of QD solar cells to date is 16.6% [50].

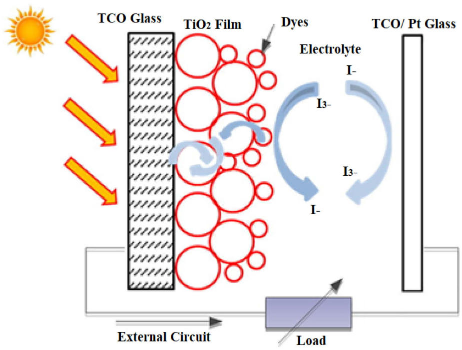

Figure 3.16 Dye-Sensitized Photovoltaic Cells

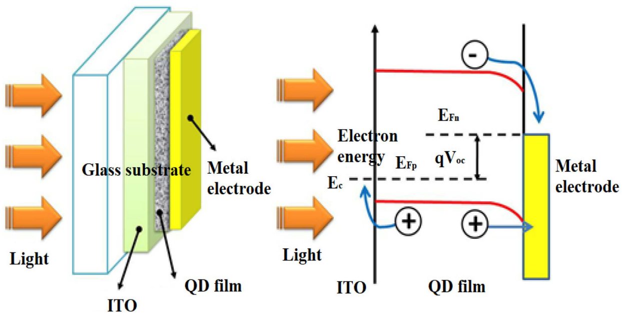

Figure 3.17 Quantum Dots Photovoltaic Cells

3.8.4 Fourth Generation of Photovoltaic Cells

A combination of low-cost and flexible polymer thin films is presented in the Fourth-generation photovoltaic cells. These types of cells are made with the stability of metal nanoparticles and metal oxides, carbon nanotubes, graphene, and their byproducts. They are also referred to as "hybrid inorganic cells" or "nano photovoltaics".This type of PV cell has the potential to become the future of photovoltaic cells.

3.8.4.1 Graphene-Based Photovoltaic Cell

Graphene is considered a potential nanomaterial for the future. Graphene synthesis (Figure-3.18) consists of mainly two types of methodologies, one is bottom-up and the other is top-down methods. In the top-down approach, starting from graphite by solid, liquid, or electrochemical exfoliation graphene sheets are produced. On the other hand, In the bottom-up approach graphene is produced from molecules by chemical vapor deposition [50]. Due to their high carrier mobility, more flexibility, environmental stability, low resistivity and transmittance, and 2D lattice packing properties graphene-based materials are being considered for use in PV devices instead of existing conventional silicon materials. The energy conversion efficiency is 20.3% for graphene-based perovskite solar cells and 10% for bulk heterojunction organic solar cells.

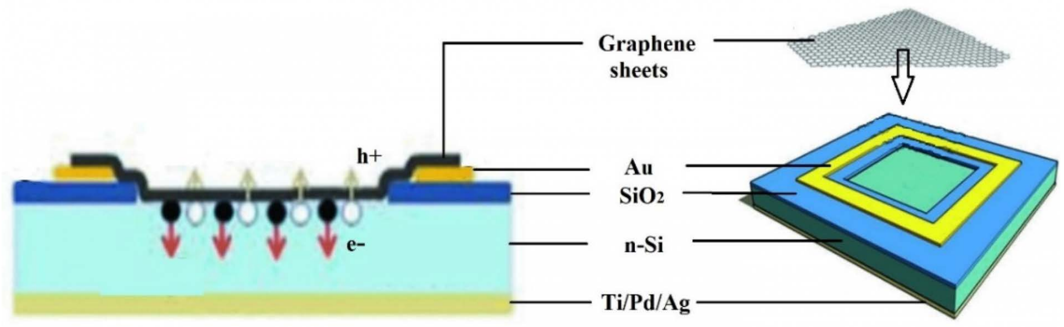

Figure 3.18 Graphene-Based Photovoltaic Cells

3.9 Photovoltaic System

A photovoltaic system can convert solar energy to electrical energy through the photovoltaic effect and supply it to a given load. The system structure is very flexible. PV modules are the main building blocks for electric energy production. PV systems can be broadly classified into two major groups [51]

3.9.1 Stand-Alone PV System

These systems are isolated from the electric distribution grid. It includes a charge controller, an inverter, and a storage system all the elements are necessary to serve AC appliances in a common household or commercial application. The number of required components in the standalone system will depend on the given amount of load.Figure-3.19 represents the schematic diagram of a stand-alone PV system.

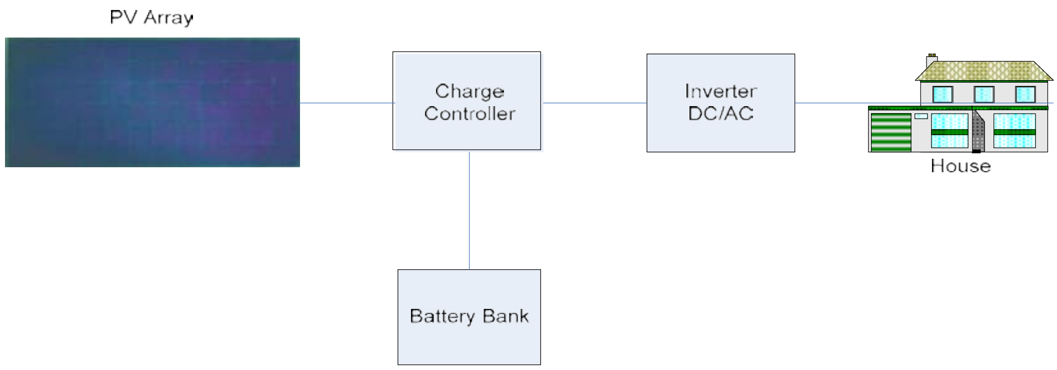

Figure 3.19 Stand-Alone PV System

3.9.2 Grid-Connected PV System

These systems are directly coupled to the electric distribution network and do not require battery storage. Figure-3.20 describes the basic system configuration of a grid-connected PV system. Electric energy is either sold or bought from the local electric utility depending on the local energy load and the solar resourcevariation during the day, an inverter is required to convert DC currents to AC currents.

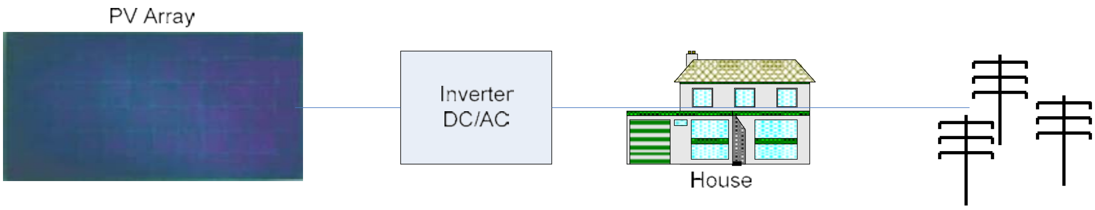

Figure 3.20 Grid-Connected Solar System

Other than the above two a hybrid system may be possible where battery storage or a generator (or both) can be combined with a grid connection for additional reliability and scheduling flexibility (at additional cost) [51].

3.10 PV System Applications

- ➔ Electrification of homes and buildings
- ➔ Autonomous lighting
- ➔ Agricultural applications
- ➔ Pumping and water treatment
- ➔ Signaling and communications
- ➔ Other specific applications: hydrogen production, environmental applications, oxygenation of the water, cathodic protection of pipelines, space applications or supply of electric vehicles, etc.

3.11 Conclusion

In this chapter, the concept of the solar cell, its characteristics, an overview of the PV system, and a detailed discussion of solar PV technology are presented. The production of solar energy, from the available sunlight, and its usage is more clean, safe, and more efficient. Among all the PV technology m-Si and p-Si are the two most common and commercially available which are used in this study. A detailed explanation of how the study is performed is included in the next chapter.

Chapter-4

Overview of PVsyst Software

4.1 Introduction

In the previous chapters, we have discussed the current energy scenario of India and why we need to shift from our conventional energy sources (Chapter-1). Next, a brief explanation of the problem statement and the literature review is presented in Chapter-2. Chapter-3 Presents a detailed concept of Solar PV technologies & their characteristics. Now, to continue our work we need to present a techno-economic analysis of the different cities according to the meteorological data. For this, we need PVsyst software. In this chapter, a detailed overview of the PVsyst software is presented.

4.2 About the Software

PVsyst is one of the oldest software in the solar energy sector. In 1992 a graduate of the University of Geneva André Mermoud obtained invented. PVsyst is a PC software available for Windows only. It can deal with grid-connected, stand-alone, and pumping PV systems, which include satellite meteodatabses and PV systems components databases. Other than that it has general solar energy tools. PVsyst focuses on a complete and precise study, sizing, and data analysis of PV systems. Here PVsyst software version 7.3.1 is used.

4.3 Features of the PVsyst Software

➔ Complete database of PV Module, Inverter & Meteo data from Solcast, Meteonorm, NASA-SSE & many others.
➔ Simulation of the aging effect of solar modules.
➔ Model storage systems.
➔ Probabilistic approach.
➔ Import PV Module, Meteorological & solar Inverter data manually.
➔ Shadow Analysis using 3D models.
➔ Design simulation of Grid-connected Standalone, Solar Pump, and DC Grid systems.
➔ Economic evaluation.

4.4 Overview of PVsyst

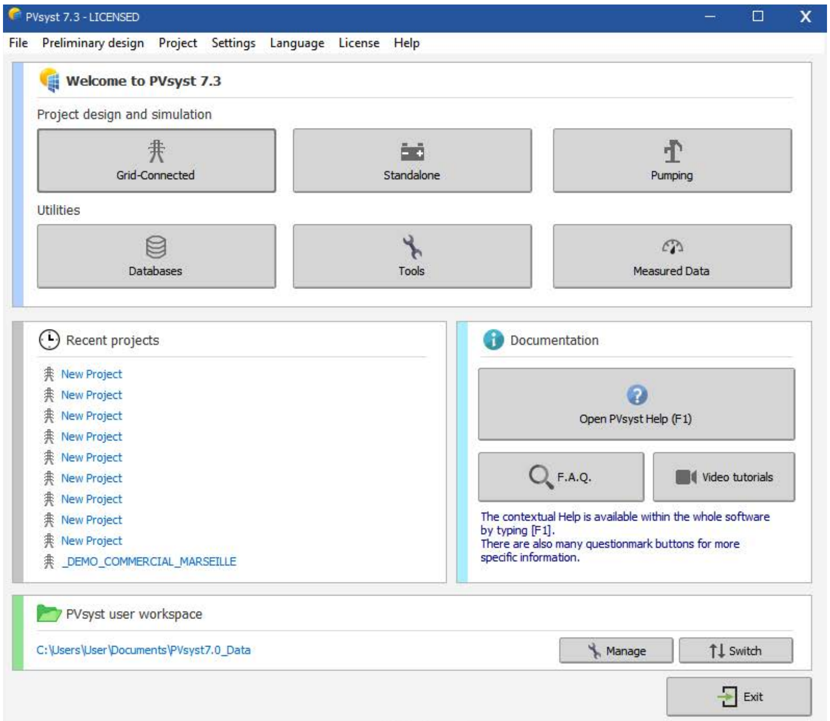

Figure 4.1 Overview of PVsyst Software

When you first open the PVsyst software there are two main parts one is “Project design and simulation” (Figure-4.1) this section is used for the complete study of a project. It involves the choice of meteorological data, system design, shading studies, loss determination, and economic evaluation. The simulation is performed over a full year in hourly steps and provides a complete report and many additional results. The other part is “utilities” Which consist of databases and tools.

4.5 Project design and simulation

Project design and simulation consist of three sections

- ➔ Grid Connected
- ➔ Stand Alone
- ➔ Pumping

4.5.1 Grid Connected System

In this section, a system can be designed linked to the grid, by default the grid works as an unlimited consumer. Add load profiles of self-consumption and grid storage to handle self-consumption.

4.5.2 Off Grid System

In this section a system can be designed which does not link to the grid hence it is an off-grid system, defined primarily by the user's needs.

4.5.3 Pumping System

In this section, an off-grid system can be designed for pumping systems, defined by the user's needs in the water.

4.6 Utilities

Utilities consist of three section

- ➔ Databases
- ➔ Tool
- ➔ Measured Data

4.6.1 Databases

4.6.1.1 Meteodatabase

Databases of meteorological data of geographical sites through different satellites. These databases can be used to generate synthetic hourly data files, comparison of meteorological data, and also can import meteo data from several predefined sources or a custom file made by the user in a proper format.

4.6.1.2 Component Database

Database management of manufacturers and PV components, including PV modules, Inverters, Regulators, Generators, Pumps, etc.

4.6.2 Tools

Contains a set of tools to display tables and graphs of meteo data or solar geometry, parameters, irradiation model, PV-array behavior under partial shadings, module mismatch, optimizing tools for tilt angle orientation, aging model, etc.

4.6.3 Measured Data

This part permits the import of measured data in almost any ASCII format, to display tables and graphs of the actual performances, and to compare with the simulated variables. This part analyses the real-time parameters of a PV system and identifies even very small irregularities [52]. There are also some specific tools useful when dealing with solar energy systems which we will discuss in the next chapter.

4.7 How to Create a Project in PVsyst Software

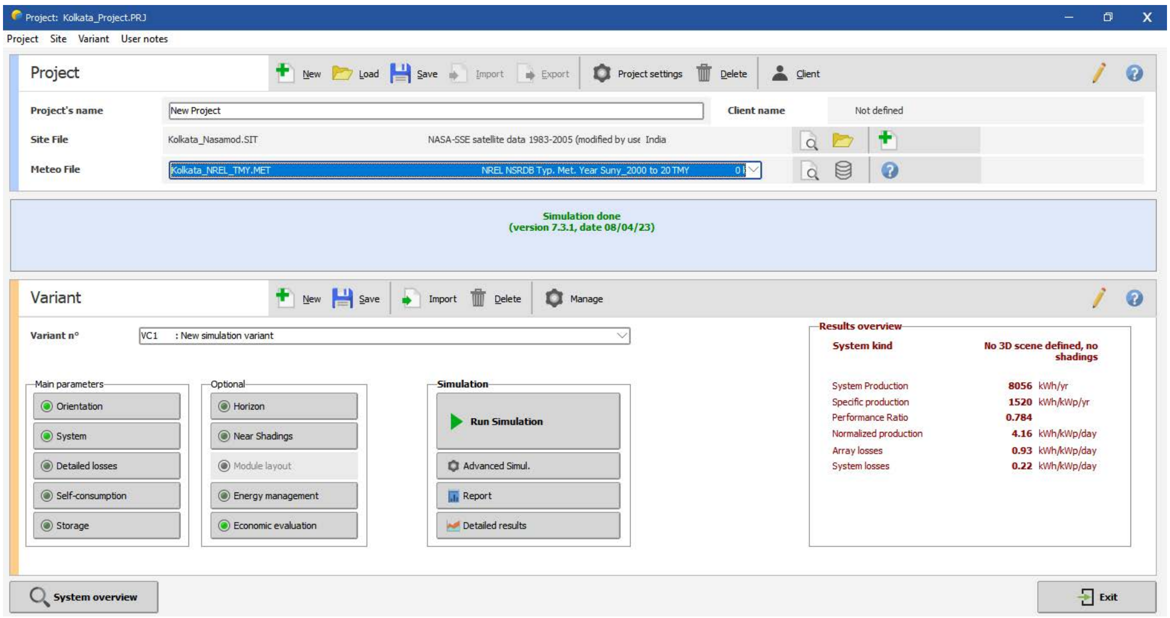

Figure 4.2 Parameters of PVsyst Software

➔ Step 1: Location

Define the location where you want to set up your PV project you can define it direct from google earth map or by manually putting the latitude and longitude of the location Import meteorological data such as GHI, GNI, wind speed, temperature, relative humidity, etc from various meteorological database such as meteonorm, NASA SSE, solcast, etc.

➔ Step 2: Orientation

Define the azimuthal and tilt angle of the module

➔ Step 3: System

Choose the projet power capacity or area, PV module type panel size, inverters, DC size, string lengths, etc.

➔ Step 4: Detailed Losses

There are various loss parameters such as soiling loss, module mismatch loss, LID loss, aging, ohmic loss, etc.

➔ Step 5: Simulation

Once the system parameters have been defined, click on “Run Simulation”. Upon completion of the simulation, a report will be available for viewing and printing. In addition, the simulation settings screen allows you to change the time frame of the simulation (from one day to one year), as well as export hourly values of various parameters including energy, inverter efficiency, PV array’s electrical behavior, and more.

There are a few other optional parameters such as the horizon, near shading, module layout, economic evaluation, etc. where you can specify more accurate results for the project simulation. Figure-4.3 represents the flow chart of project creation in PVsyst software.

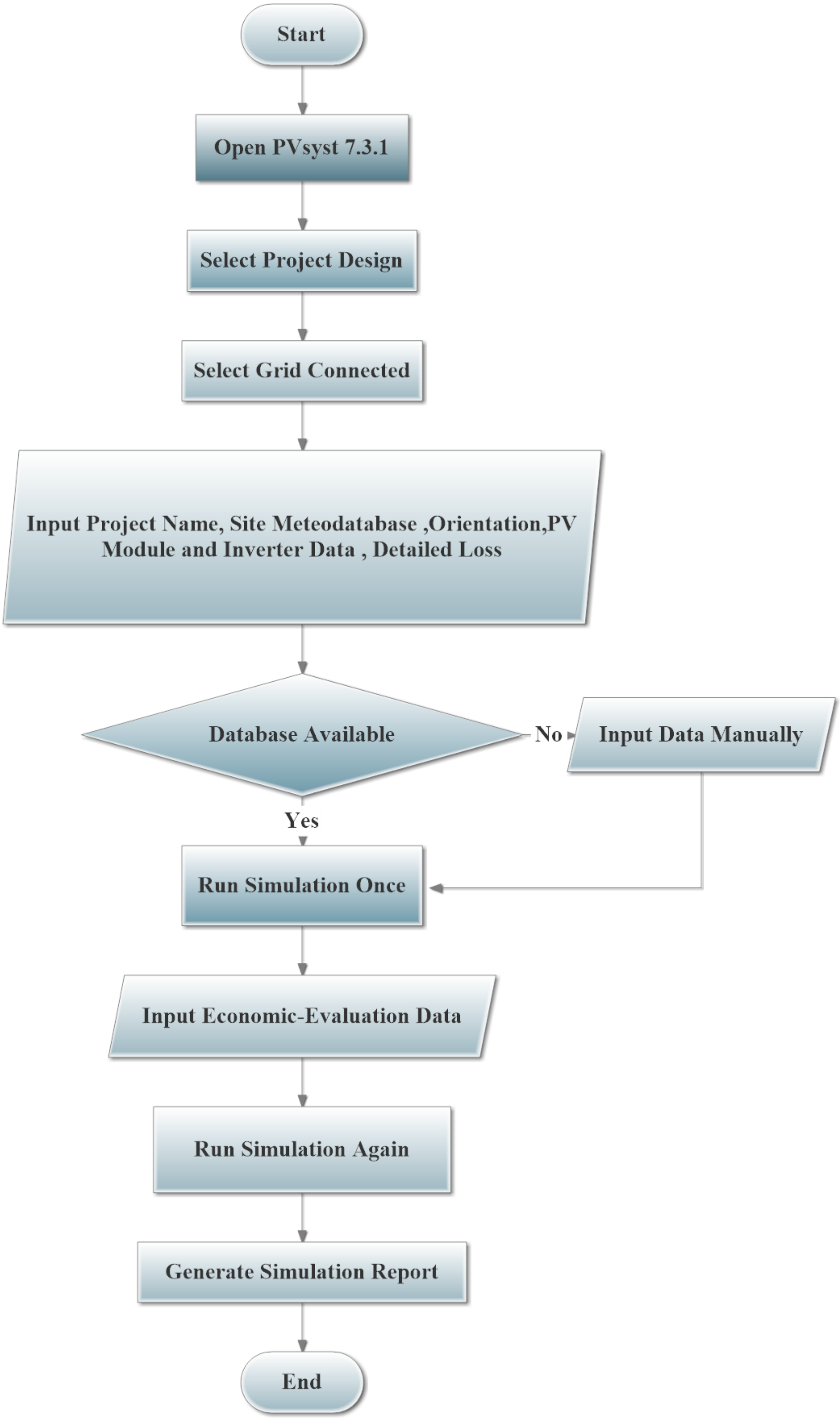

Figure 4.3 Process Chart of Creating a Project in PVsyst Software

4.8 The objective of using the PVsyst software

The main objective of using this software is to study the economic analysis of a power plant for different locations in different climatic regions of India. From the simulation result, we can compare the output parameters such as ROI, payback period, energy production cost, and Saved carbon emission. These parameters help to predict a certain type of solar panel for a specific location.

4.9 Limitation of PVsyst software

- ➔ Complicated to use for new users it requires proper training to operate this software efficiently.
- ➔ The width of the pitch and collector are not mentioned in the final generated report.
- ➔ No option to nullify the temperature coefficient in the module. PAN file.
- ➔ Limited optimization capabilities.
- ➔ Cannot do 3D modeling.

4.10 Conclusion

In this chapter, a brief explanation of the PVsysts software is given. This will give us an idea of how to use the software and what are basic features of this software as well as its limitations. In the next chapter (Chapter-5) we will show how to make a simulation report using this software for a specific panel for a specific location along with loss factors, system orientations, and economic evaluations in detail.

Chapter-5
Experimental Setup & Methods

5.1 Introduction

Before we start the measurement we need to set up the circuit for two different types of PV modules. Other than that we need to set up the PVsyst software for the simulation purpose. Here in this chapter, a brief explanation of the experimental setup and how the data has been taken is given followed by the details of used apparatuses.

5.2 Experimental Apparatus

5.2.1 Specification of PV Modules

In the experiment, we used two types of PV modules one is the m-Si PV module (Figure-5.1) and the other one is the p-Si PV module (Figure-5.2). The detailed electrical properties of the modules as per manufacturer are listed in Tables 5.1 & 5.2 respectively.

Model no.	CNC 165×165-6
Maximum power, P_{mpp}	4.5 W_P
Optimum operating voltage, V_{mpp}	6 V
Optimum operating current, I_{mpp}	0.75 A
Open circuit voltage, V_{OC}	7.2 V
Short circuit current, I_{SC}	0.83A
Temperature coefficient of I_{SC}, α	+0.06±0.01 %/°C
Temperature coefficient of V_{OC}, β	-155±10 mV/°C
Temperature coefficient of P_{mpp}, γ	-0.5±0.05 %/°C

Table 5.1 Specifications of m-Si PV module at STC condition as per manufacturer data

Model no.	BPL EC-2463
Maximum power, P_{mpp}	1.3 W_P
Optimum operating voltage, V_{mpp}	7.5 V
Optimum operating current, I_{mpp}	0.17 A
Open circuit voltage, V_{OC}	9.5 V
Short circuit current, I_{SC}	0.12 A
Temperature coefficient of I_{SC}, α	+0.03±0.01 %/°C
Temperature coefficient of V_{OC}, β	-80±10 mV/°C
Temperature coefficient of P_{mpp}, γ	-0.24±0.05 %/°C

Table 5.2 Specifications of p-Si PV module at STC condition as per manufacturer data

Figure 5.1 Monocrystalline PV Module

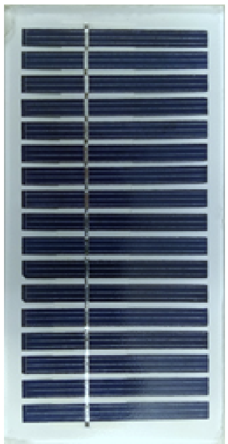

Figure 5.2 Polycrystalline PV Module

5.2.2 Resistor Board

The embedded resistor circuit board (Figure-5.3) in the range of 0 Ω to 1MΩ with an accuracy level of ±1% and a power rating is 0.5 Watts used to measure the required resistance.

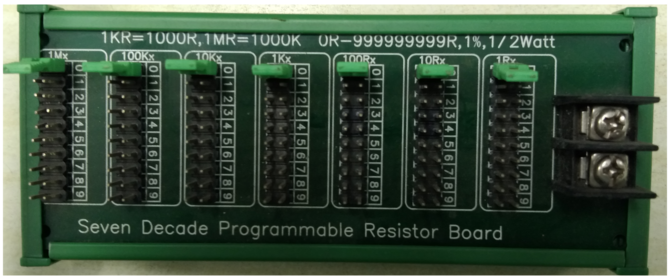

Figure 5.3 Resitor Board

5.2.3 Voltage Regulator

The AE DIMMERSTAT voltage regulator (Figure-5.4) manufactured by automatic electric limited India, used to control the halogen light intensity. The output voltage range of the voltage regulator is 0-240V.

Figure 5.4 Voltage Regulerator

5.2.4 Thermocouple

Measurement of modules temperature performed using K- type thermocouple with ±0.5◦C accuracy level (Figure-5.5). Two thermocouples were attached to the backside in the middle of the module and another was in a corner position for better temperature measurement.

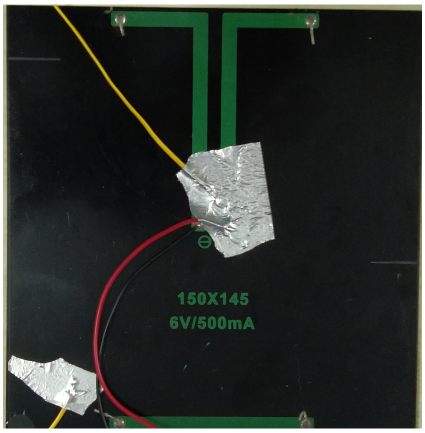

Figure 5.5 Thermocouple

5.2.5 Radiation Measurement Sensor or Solarimeter

The TES 1333 solar power meter (Figure-5.6) is used for radiation measurement on the horizontal surface level of the module surface. In this instrument range of irradiation, measurement is up to 2000 w/m^2 with a spectral response of 400-1100 nm with an accuracy of ±10 w/m$^{2.}$

Figure 5.6 Radiation Sensor

5.2.6 Data Logger

Agilent 34970A data acquisition system (Figure-5.7-5.8) used for continuous data monitoring and recording of PV characteristics with different conditions. The instrument was logged and stored data every five seconds.

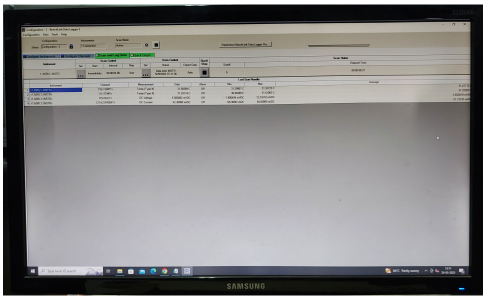

Figure 5.7 Recording of Data

Figure 5.8 Data Logger

5.2.7 Light Source

A Philips 1000W halogen lamp (Figure-5.9) used as a source of constant light intensities of 10 -1200 w/m^2 with the help of a voltage regulator in the experiment.

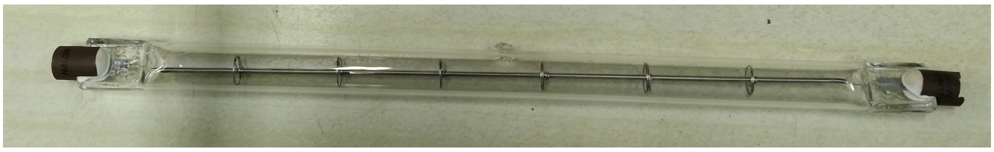

Figure 5.9 Philips 1000 W Halogen lamp

5.3 Circuit Diagram

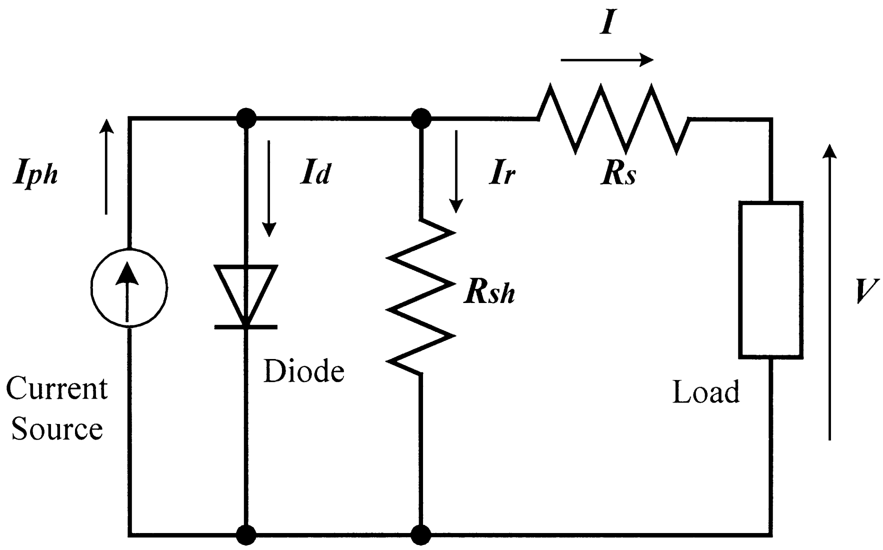

Figure 5.10 Equivalent circuit for PV modules

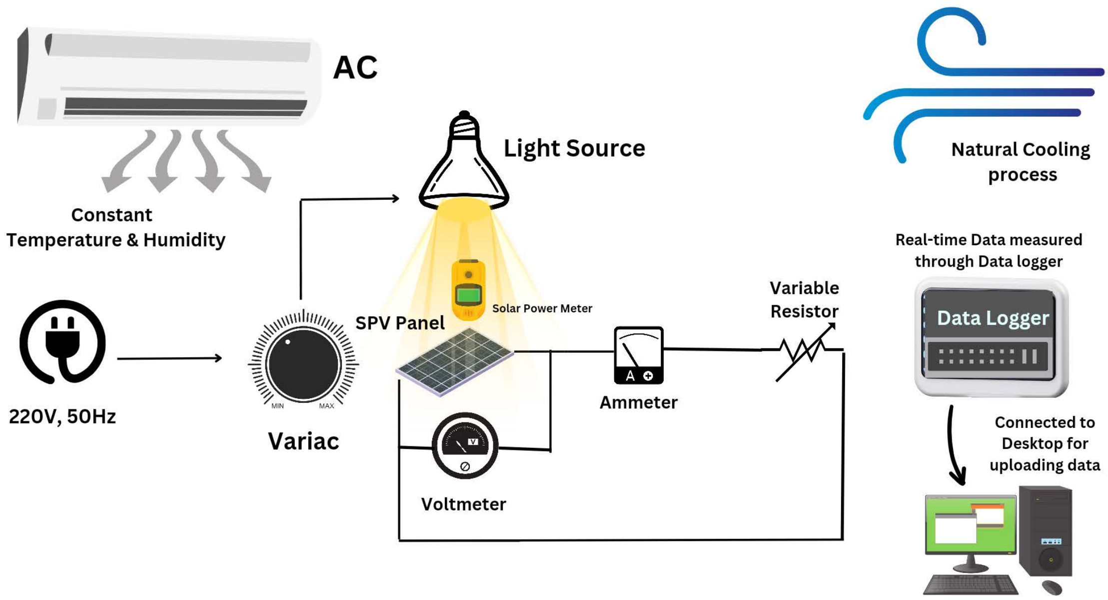

Figure 5.11 Schematic Circuit Diagram of Experimental Setup

5.4 Experimental Procedure

- ➔ Switch on the halogen lamp.
- ➔ Set the desired radiation intensity by a voltage regulator.
- ➔ Measure the light intensity using the Solar Power meter.
- ➔ Place the solar PV module under the light.
- ➔ Set a certain resister value in the resister board.
- ➔ Start the data logger and record the data.
- ➔ Due to the heat energy generated by the light source the temperature of the panel will increases. As per the temperature and intensity corresponding current and voltage data are recorded.
- ➔ Then when the cell temperature reaches 60^0C.Switch off the light save the recorded data file and imported it. CSV file from the data logger software.
- ➔ Repeat the process for different intensity and resistance sets.
- ➔ From the data set voltage vs. current, power vs. voltage, and efficiency vs. temperature are plotted for different radiation intensities for two types of PV modules.

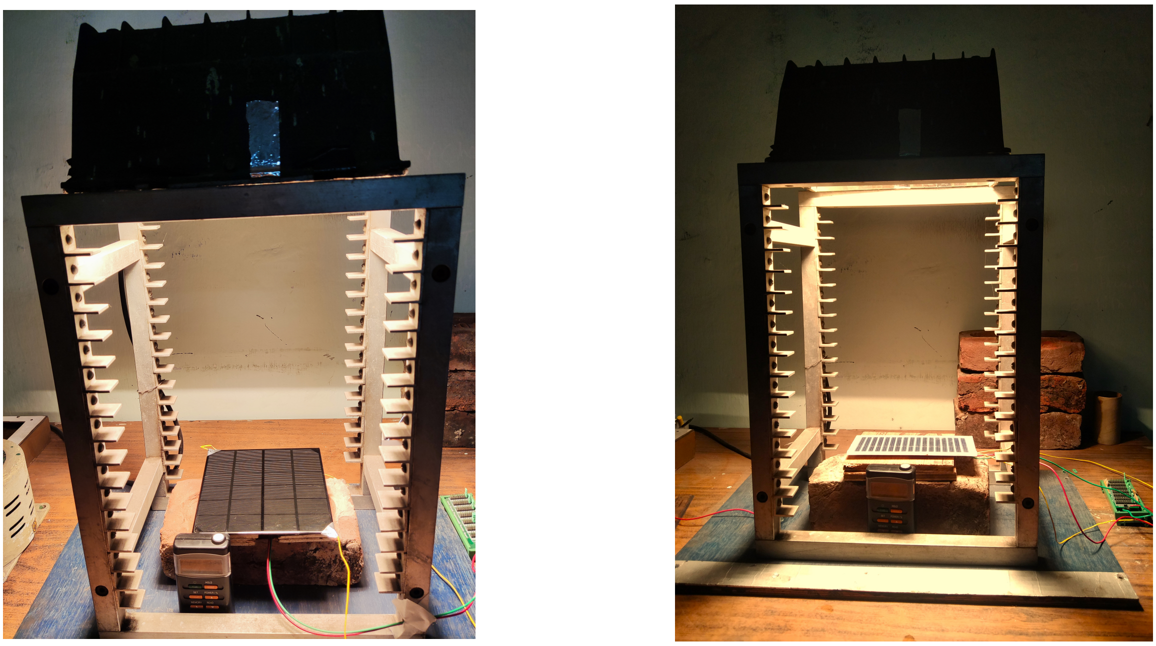

Figure 5.12 Experimental Setup

Figure-5.11 represents the schematic circuit diagram of the experimental setup. Figure-5.12 shows the experimental setup. During the measurement process, a constant room temperature and humidity are maintained by operating an air conditioner machine at a constant temperature. Throughout the experiment, all the fans are switched off and all the doors were closed this is done to maintain a constant wind speed, as we assumed that throughout the process there is no variation in ambient temperature, humidity, and wind speed.

5.5 Climatic Zones

A mainland area of 3,287,263 km^2 makes India one of the largest countries in the world [53]. The geography of the Indian subcontinent is extremely diverse, ranging from deserts to snowcapped mountains and from long coasts to evergreen forests. India is bounded on the south by the Indian Ocean, southwest by the Arabian Sea, and on the southeast by the Bay of Bengal. In the northern area, there are the Himalayas. Kanyakumari is considered as the southernmost part of the Indian mainland. India is divided into 29 states & 6 federally administered union territories and a national capital territory [53]. Due to this geographical diversity, the climate is also different in every corner of the country, The Himalayan ranges in the Northern area are always covered with snow and are very cold whereas the deserts of Rajasthan are humid and hot. The percentage of rainfall is also not uniform across the country. Cherapunji in Meghalaya receives the highest amount of rainfall whereas, in the Thar desert, a very less amount of rainfall occurs. According to National Atlas & Thematic Mapping, Organisation (NATMO), the Indian subcontinent can be divided into 9 climatic zones (Figure-5.13) [54].

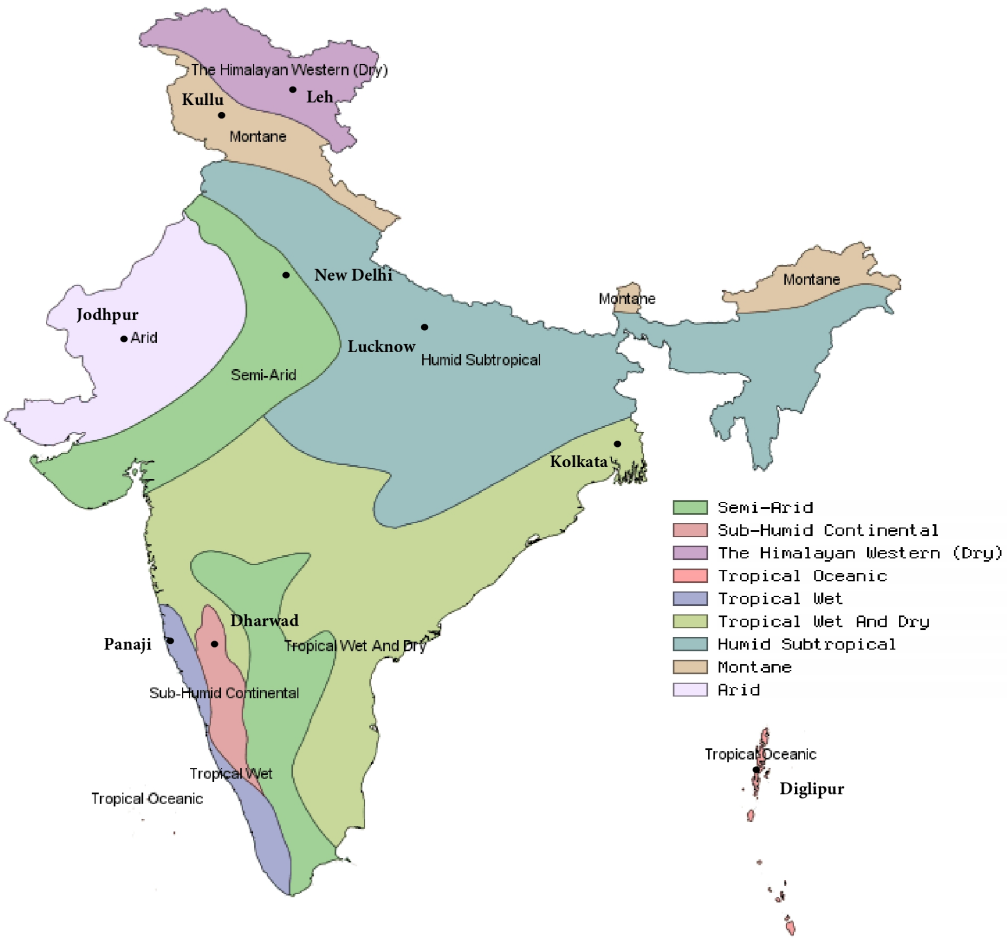

Figure 5.13 Climatic Regions of India

For an economic evaluation, we need to have meteorological data, degradation loss data, and soiling loss percentage data for each climatic zone, unfortunately, no such data have been found, so to counter this issue in each climatic zone one city is chosen for which we will do the techno-economic analysis. Table-5.3 represents each climatic zones and its corresponding chosen city.

Climatic Zone	City
The Himalayan Western	Leh
Montane	Kullu
Humid Subtropical	Bhopal
Arid	Jodhpur
Semi-Arid	New Delhi
Tropical Wet & Dry	Kolkata
Tropical Wet	Panaji
Sub Humid Continental	Dharwad
Tropical Oceanic	Diglipur

Table 5.3 Climatic Zone & Chosen City

5.6 Pricing Details

After taking the real-time data for two types of PV modules in the lab set up now we need to perform the economic evaluation for those PV panels in different climatic regions of India. For this, we are going to design a 5 kWp grid-connected solar power plant with a 325 Wp m-Si and p-Si solar PV module using PVsyst software. Next, we need to set the price of panels, inverters, and other maintenance costs and tariff rates. We assumed a fixed price rate in all the climatic zones for two types of PV modules and inverters as per the current market value. The variations in pricing will be in the maintenance section. Let's take an example, say we are going to install a solar module in Kolkata as well as in Panaji, Goa between these two locations the support for module cost will be greater in Panaji, Goa compared to Kolkata as Panaji is situated near the ocean as a result it is a windy area so we need to give more support to the PV module. Similarly, the labor maintenance cost will be higher in Bangalore or Delhi compared to Kolkata, since Kolkata is one of the cheapest cities in India. So, after considering every aspect a detailed research & survey of the market rate a price table [Table-5.4] is produced. This table will be used for economic evaluation. Table-5.5 shows the benchmark rates and Feed tariff rates for each chosen city as per government guidelines.

Climatic Zone	City	Solar Panel Company	Solar Panel Size	Solar Panel Type	Solar Panel Cost (INR/Wp)	Inverter Company	Inverter Cost (INR/Wp)	Support For Module Cost(INR/Wp)	Settings Cost (INR/Wp)	Transport Cost (INR/Wp)	Engineering Cost (INR/Wp)	Total Cost (INR/Wp)
The Himalayan Western	Leh	GCL	325 Wp	Mono	28	Delta Energy	5	3	3	2.5	2.2	43.7
				Poly	27		5	3	3	2.5	2.2	42.7
Montane	Kullu			Mono	28		5	3	3.2	1.2	2.2	42.6
				Poly	27		5	3	3.2	1.2	2.2	41.6
Humid Subtropical	Bhopal			Mono	28		5	1.5	2	0.6	2	39.1
				Poly	27		5	1.5	2	0.6	2	38.1
Arid	Jodhpur			Mono	28		5	1.5	2	0.7	2	39.2
				Poly	27		5	1.5	2	0.7	2	38.2
Semi-Arid	New Delhi			Mono	28		5	1.5	2	0.6	2	39.1
				Poly	27		5	1.5	2	0.6	2	38.1
Tropical Wet & Dry	Kolkata			Mono	28		5	1.5	2	0.5	2	39
				Poly	27		5	1.5	2	0.5	2	38
Tropical Wet	Panaji			Mono	28		5	2.5	3	1	2	41.5
				Poly	27		5	2.5	3	1	2	40.5
Sub Humid Continental	Dharwad			Mono	28		5	1.5	2.5	0.7	2	39.7
				Poly	27		5	1.5	2.5	0.7	2	38.7
Tropical Oceanic	Diglipur			Mono	28		5	3	3.2	2.6	2.5	44.3
				Poly	27		5	3	3.2	2.6	2.5	42.3

Table 5.4 Pricing Details for Simulation

Climatic Region	City	Tariff Rate (INR/kWh)	Bench Mark Rate (INR/Wp)	Tariff Rate Cost Reference	Benchmark Cost Reference
The Himalayan Western	Leh	6.47	49.1	[55]	[63]
Montane	Kullu	3.79	49.1	[56]	
Humid Subtropical	Bhopal	4.06	44.64	[57]	
Arid	Jodhpur	3.94	44.64	[58]	
Semi-Arid	New Delhi	7.04	44.64	[59]	
Tropical Wet & Dry	Kolkata	3.46	44.64	[60]	
Tropical Wet	Panaji	4.68	44.64	[61]	
Sub Humid Continental	Dharwad	4.02	44.64	[62]	
Tropical Oceanic	Diglipur	4.68	49.1	[61]	

Table 5.5 Tariff Rate & Benchmark Cost for Each City

5.7 Meteorological Data

Now in PVsyst software, there are various inbuilt meteorological databases such as Meteronom, NASA SSE, Solcast, etc. but some of them are paid whereas some of them have data up to 2005 or 2015. For an accurate economic evaluation, we need to give updated climatic data. To do this we took the satellite data from the NSRDB data viewer [64] where we took the GHI, GNI, Ambient temperature, Relative humidity, and Wind speed for 2017-2019. The climatic data for Kolkata which we used is shown in Table 5.6. For the other city, the data are attached in Annexure-I.

Climatic Region	City	Month	Average GHI (W/m^2)	Average DHI (W/m^2)	Average Temperature (^0C)	Average Relative Humidity (%)	Average Wind Speed (m/s)
Tropical Wet & Dry	Kolkata	January	182.2433	78.98566	17.30972	61.7386	2.108681
		February	206.3046	88.03075	22.50263	56.78846	2.185069
		March	236.7854	103.0703	26.69866	60.7469	2.135995
		April	252.7106	123.9269	30.39148	66.26163	2.221296
		May	251.5941	135.2473	31.39597	70.53088	2.118519
		June	199.731	129.1255	30.18236	82.2344	2.029745
		July	159.5784	113.8109	29.0082	89.17257	2.120718
		August	169.2267	118.3625	28.47285	92.19511	2.16794
		September	166.2579	108.2875	27.90532	92.40583	2.270718
		October	166.4745	91.68683	26.22155	85.60586	2.292361
		November	174.5833	81.03148	22.36148	80.24211	2.124884
		December	154.9229	76.43817	17.92065	76.44715	2.019097

Table 5.6 Meteorological Data for Kolkata (2017-2019)

5.8 System Design in PVsyst Software

➔ Open PVsyst software 7.3.1 and click on the "Grid Connected" system as shown in Figure-5.14.

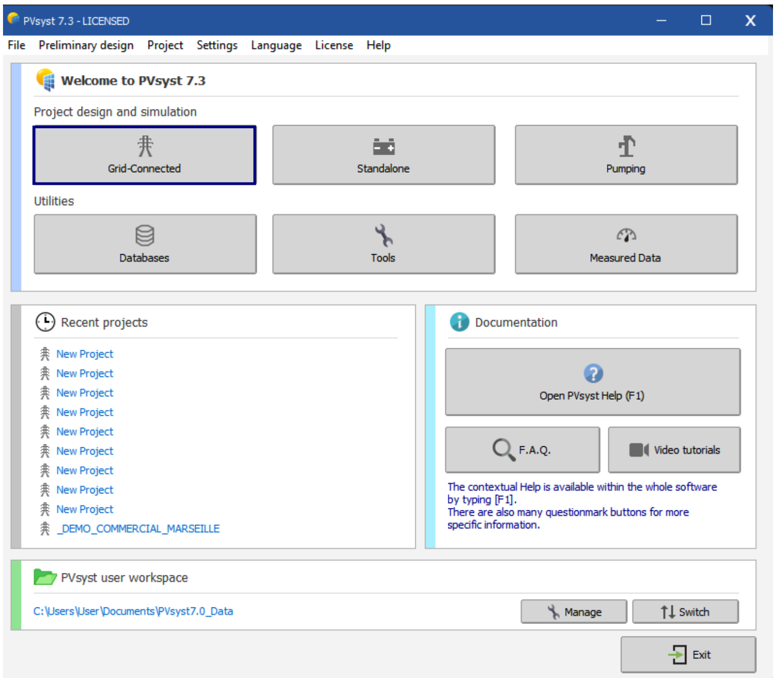

Figure 5.14 PVsyst Grid Connected System

➔ Name the new project and click on the plus sign in the meteo file section as shown in Figure-5.15.

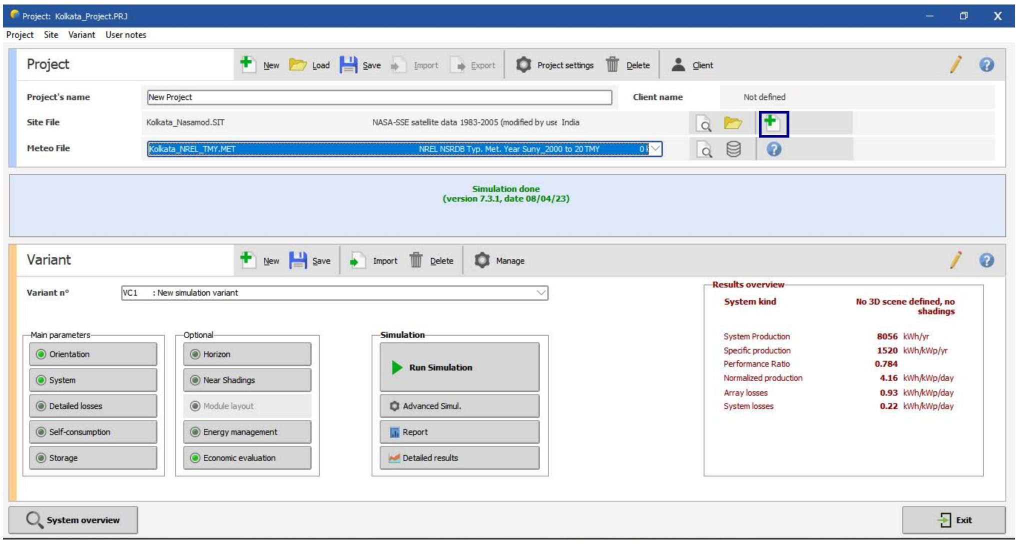

Figure 5.15 PVsyst Grid Connected System

➔ Open Google Earth map, in the search box, write the desired city or location after the screen shows the location click on "Accept selected point" as shown in Figure-5.16.

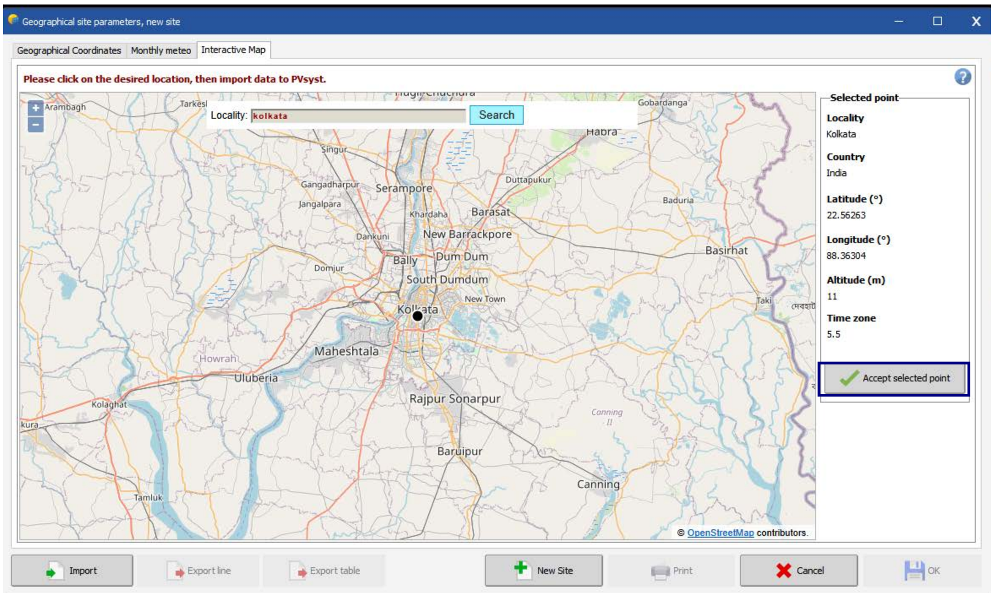

Figure 5.16 Location in PVsyst

➔ Then a new page will open where latitude, longitude, and height will be auto-filled. Then in the meteorological section select NASA-SSE as shown in Figure-5.17.

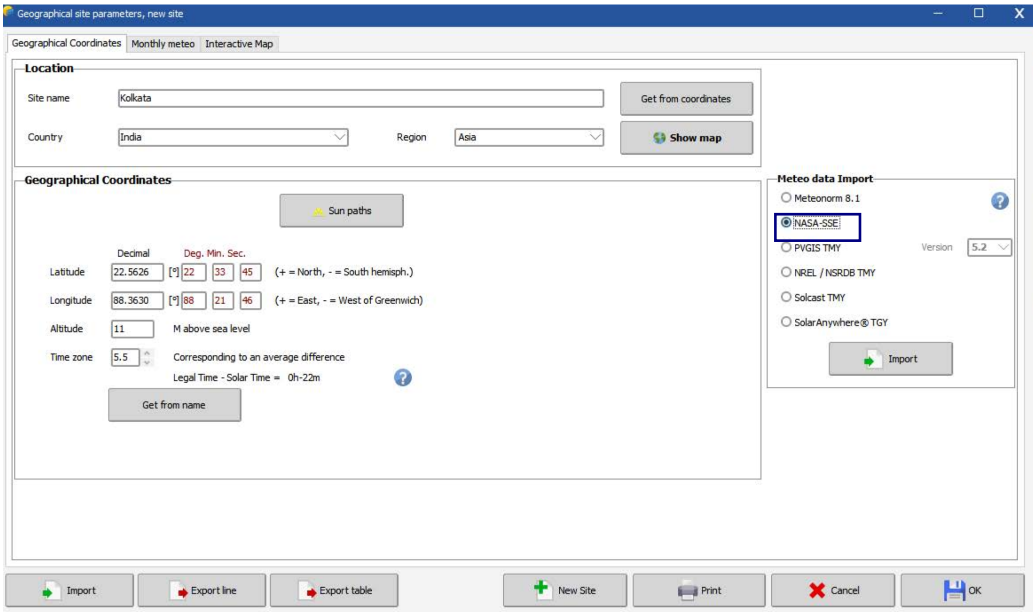

Figure 5.17 Geographical Coordinate in PVsyst

➔ After that, a new page will open then copy the updated data according to Table-5.6 and paste it into the table as shown in Figure-5.18. For relative humidity, you can't paste you need to write it manually according to the monthly data. Select the unit in W/m^2 format.

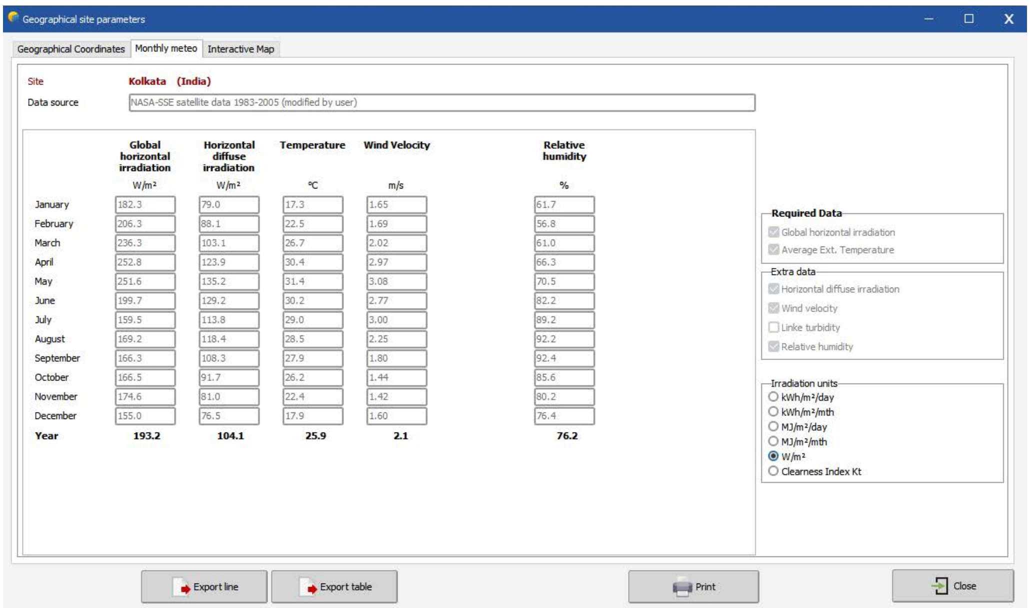

Figure 5.18 Importing Meteorological Data in PVsyst

➔ Now, save and close the file. Then open the orientation option. Select the fixed tilt plane from the drop-down menu as shown in Figure-5.19. Put the angle according to the latitude of the location. Here for Kolkata, the tilt angle is approximately 23^0

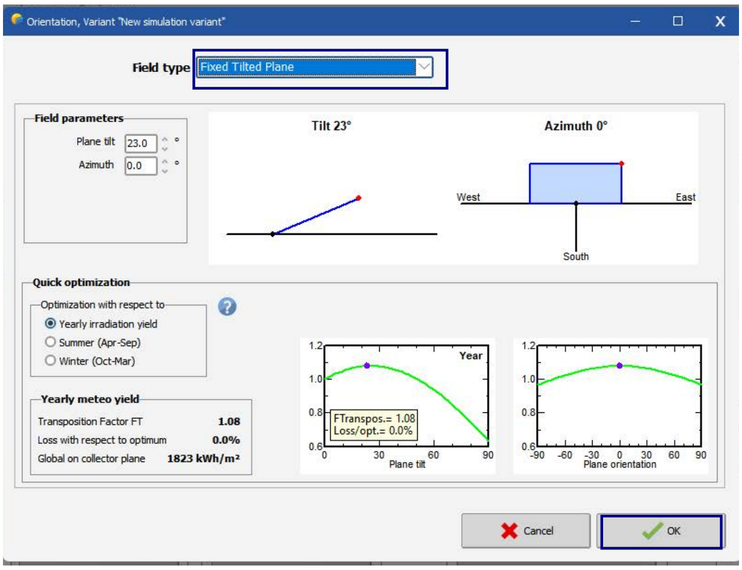

Figure 5.19 Orientation of the System in PVsyst

➔ Then Click on "OK". Put PV plant size as 5 kWp. Then open the system select PV module company as GCl, select 365 Wp 28 V Mono Crystalline PV module with model Number M6/60-325 or 365 Wp 30 V Poly Crystalline PV Module with model Number P3/60H-325, select inverter company as Delta energy, for 5.0 kWp size plant select model number 5.0 AP G3. Here the number of strings, required modules, and plant area will be initiated automatically. Check if there is any red warning or any error message that appears on the screen else click on "OK".The reference image is shown in Figure-5.20

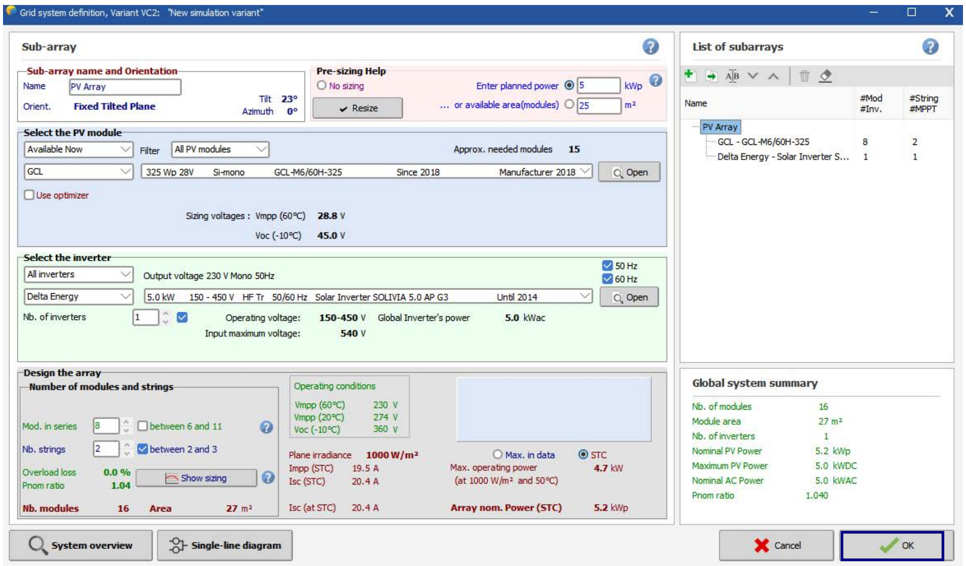

Figure 5.20 Systems in PVsyst

➔ Open the "Detailed Loss" section from the menu as shown in Figure-5.21 open soiling loss, now according to [65] the soiling loss for the Indian composite climatic zone is 1.5-5 % so, here three discreet values of soiling loss are taken maximum value (5%), minimum value (1.5%) and default PVsyst value (3%). Put one of these values then click on "OK". The rest of the parameters are left as default.

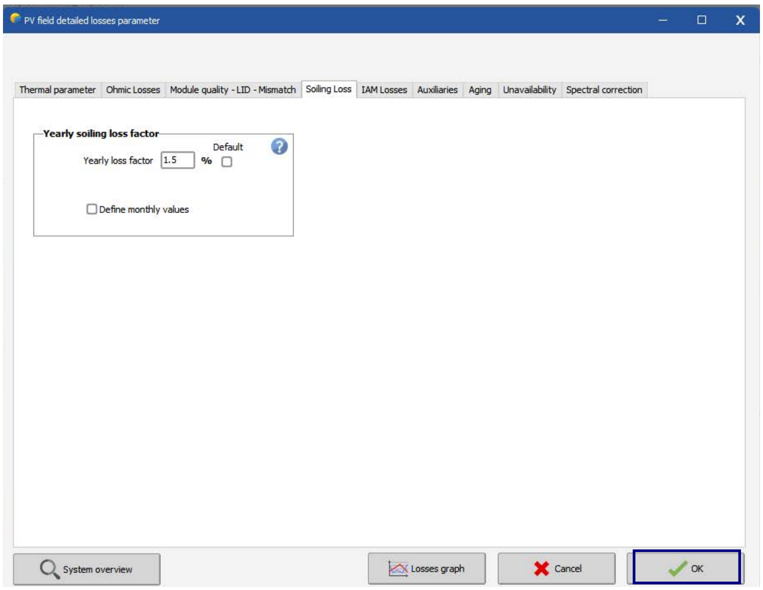

Figure 5.21 Soiling Loss in PVsyst

➔ Then run the simulation once. Save the simulation variant and then opened "Investment & Charges" in the "Economic Evaluation", section as shown in Figure-5.22 put the pricing details according to Table-5.4.

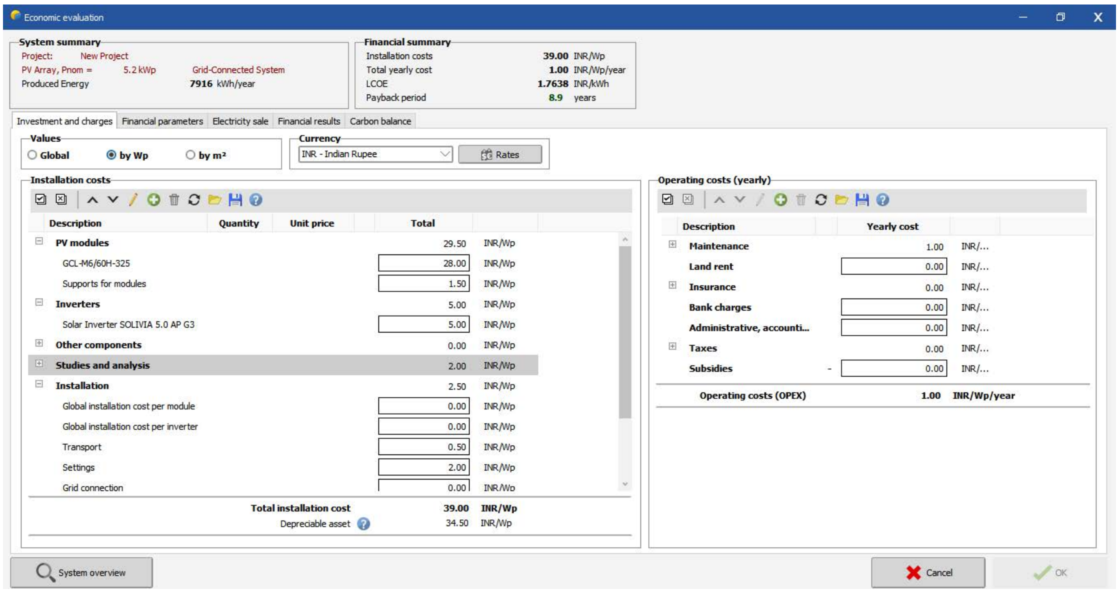

Figure 5.22 Investment and Charges in PVsyst

➔ As shown in Figure-5.23 in the “Financial Parameter” section take the project lifetime as 25 years, inflation and discount rate as zero. Here we assume that no loan is provided for this power plant all the funds are defined as own funds. The production variation (aging) or degradation loss for the m-Si module in the Indian subcontinent is 0.4 to 4.2 % [66] whereas for p-Si 0.5% to 3.5 % [67].

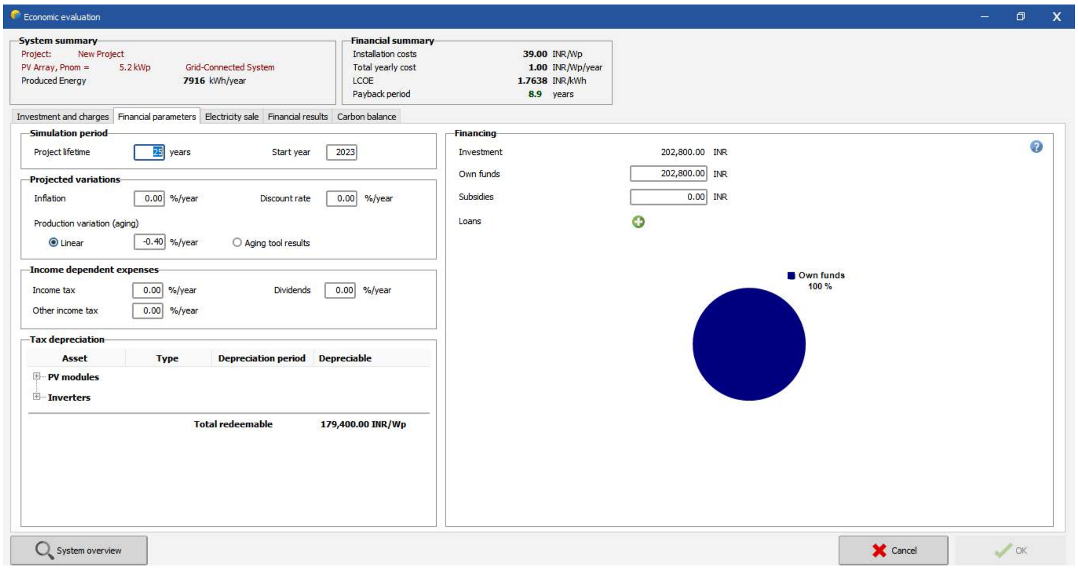

Figure 5.23 Financial Parameters in PVsyst

➔ In the electricity sale section fill the tariff rate according to Table-5.5 for different locations. Here for Kolkata, the rate is 3.46 INR/kWh (Figure-5.24). Tariff variation is taken as 1.00%, a decrease in tariff variation after the warranty is -50% means after the warranty the production power of the panel will be half compared to the new panel.

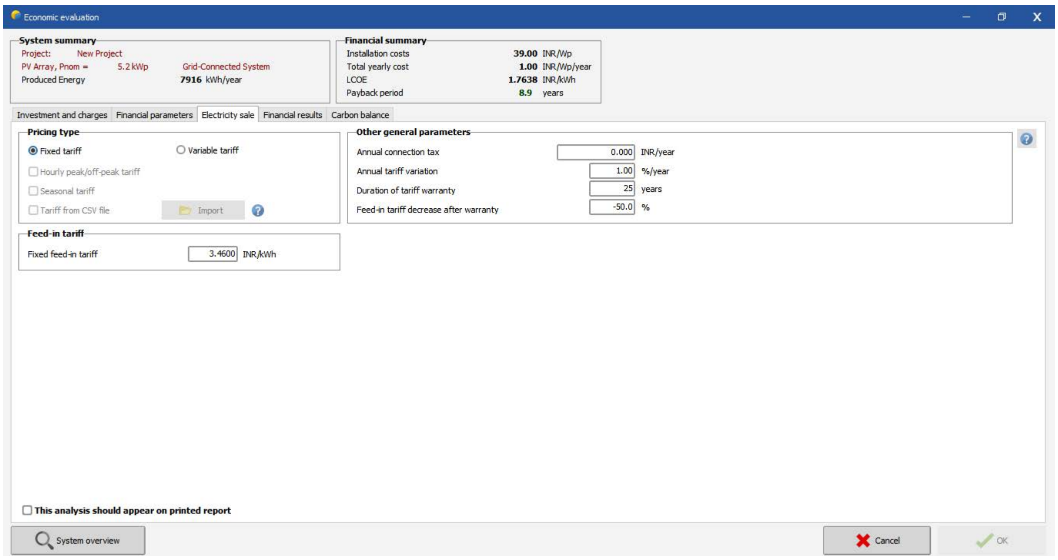

Figure 5.24 Electricity Sell in PVsyst

➔ In the "Carbon Balance" section, we considered the annual degradation as 0.9% means an excess of 0.5% loss is added to the degradation loss (0.4%) this excess loss is termed as miscellaneous loss (Figure-5.25). According to the above data, the software will automatically calculate the saved carbon emission for the system and then click on “OK”.

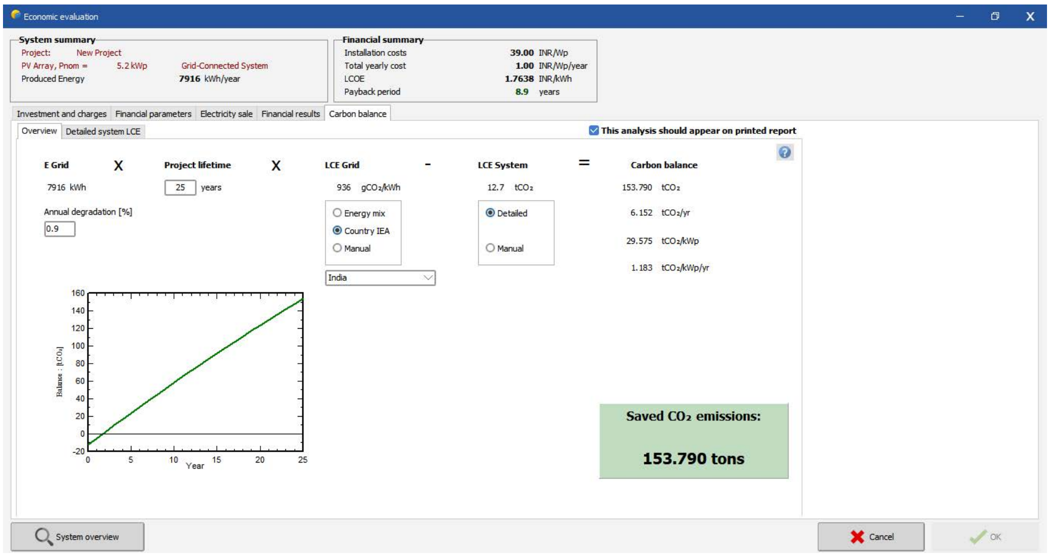

Figure 5.25 Carbon Balance in PVsyst

➔ Again run the simulation. Click on generate report a pdf report will be generated as shown in Figure-5.26. Save the report.

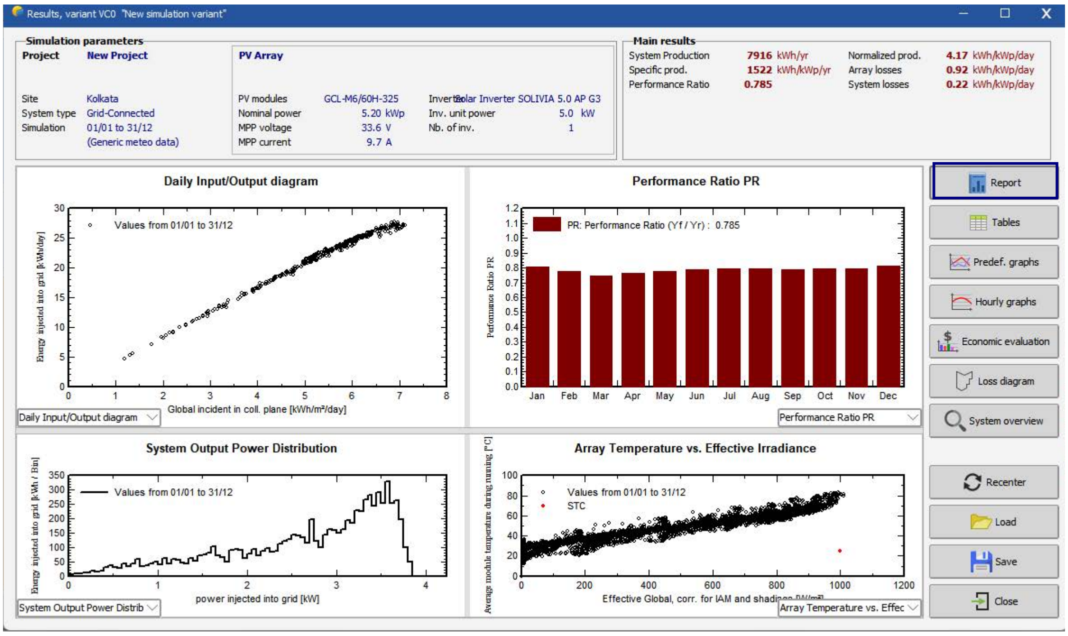

Figure 5.26 Report Generation in PVsyst

Now, repeat the entire process for different soiling loss parameters and degradation loss parameters as per Table 5.4 for the different climatic zone for two types of PV Modules. Hence a complete table will be generated which is shown in the next section.

5.9 Conclusion

In this chapter, a detailed explanation of how the real lime data has been taken and how the project report is generated using PVsyst software is provided. From the produced report a table will be generated in the next chapter and a graphical representation of the outcome will be shown which will eventually help us to analyze the result and find the solution to our stated problem.

Chapter-6
Result
&
Discussions

6.1 Introduction

This chapter analyses the data, table, and graphs obtained from the experimental and simulation methods which we already discussed in Chapter-5. The outcome of the study is presented and discussed in this chapter concerning the aim of the study, which was to determine the most suitable type of PV Module for different locations. There are two sub-aims - the first is to compare the better efficient solar PV module between m-Si and p-Si, and the second is to compare the economic analysis for these two PV modules for each chosen city in each climatic zones of India.

6.2 Average Solar Radiation in India

Solar radiation is an electromagnetic wave that is received from the sun, over a wide range of wavelengths at varying intensities. The wavelength that comes from the sun is between the intensity of 300 nm to 3000 nm called shortwave radiation. Due to its geographical position, India receives around 4-7 kWh/m^2 GHI solar irradiation per day and roughly about 1200-2300 kWh/m^2 per year as shown in Figure-6.1. Which is also referred to by [68]. Now, considering the sun's peak hours as 10-12 hours the average GHI in India roughly comes around 400 W/m^2 to 600 W/m^2 [69].

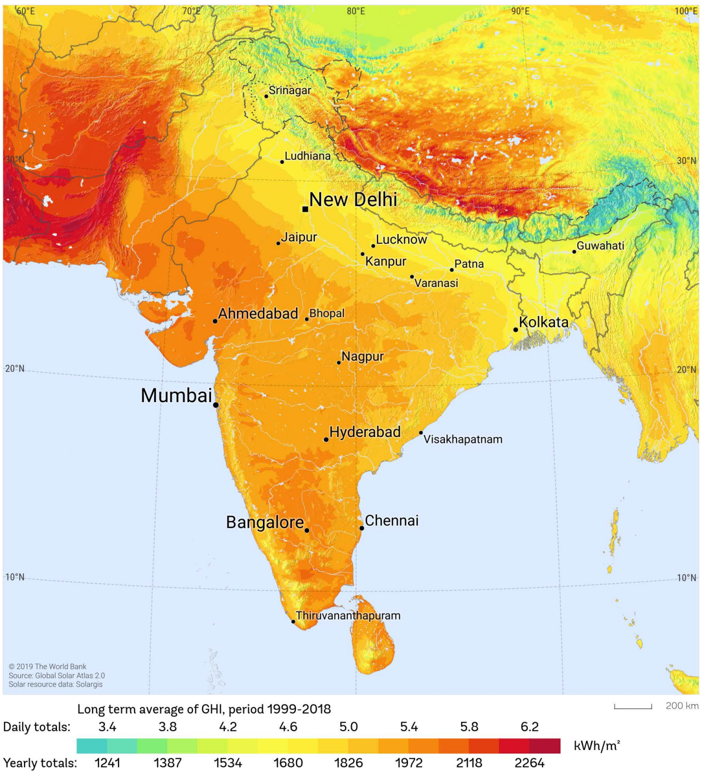

Figure 6.1 Average Solar Radiation Map for India

6.3 I-V Characteristics of Monocrystalline & Polycrystalline PV Modules

The power output of a solar PV module depends on various factors such as the material of the PV module, ambient temperature, module temperature solar radiation intensity, wind speed, humidity, air quality, etc. Temperature is one of the key factors regarding the output of the PV module. The ambient and the module temperature are interconnected to each other, with increasing one the other will also increase. Now, here Fig-6.2, Fig-6.4, and Fig-6,6 represent the I-V characteristics of m-Si PV modules for solar radiation intensity 400, 600, and 1000 W/m^2 for temperatures ranging from 20^{0}C to 60^{0}C. Similarly, Fig 6.3, Fig-6.5, and Fig-6.7 represents the I-V characteristics of the p-Si PV module with the same variation. Here we observe that for an m-Si PV module with increasing temperature, the short circuit current increases slightly and the open circuit voltage decreased significantly whereas for a p-Si PV module, both the short circuit current and open circuit voltage decrease with increasing temperature for a fixed solar radiation intensity.

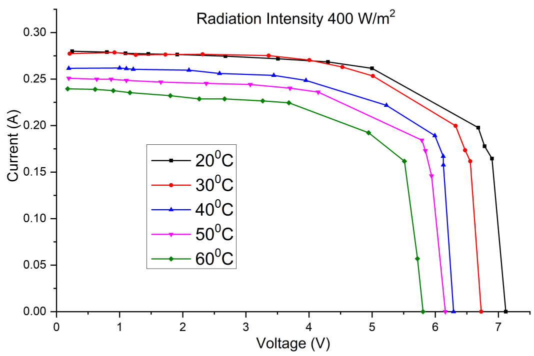

Figure 6.2 I-V Characteristics for m-Si PV Module

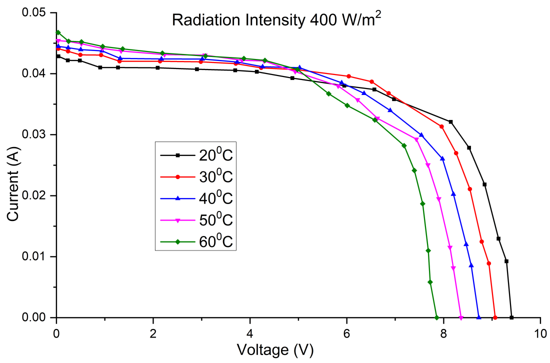

Figure 6.3 I-V Characteristics for p-Si PV Module

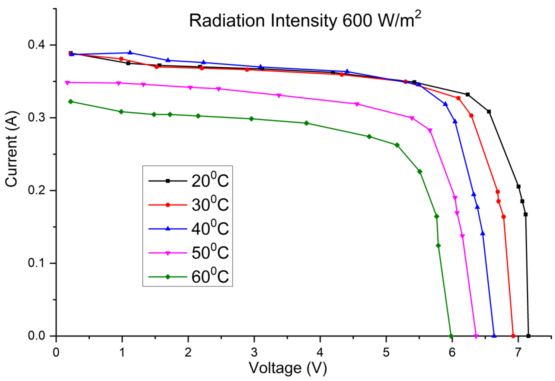

Figure 6.4 I-V Characteristics for m-Si PV Module

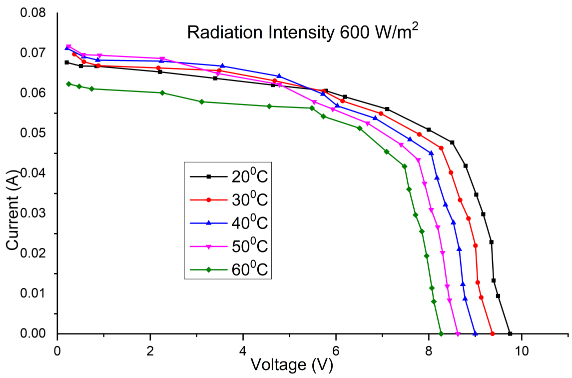

Figure 6.5 I-V Characteristics for p-Si PV Module

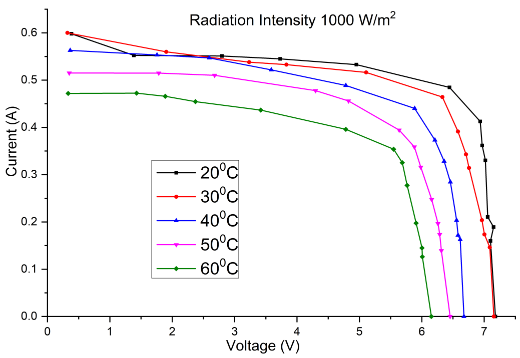

Figure 6.6 I-V Characteristics for m-Si PV Module

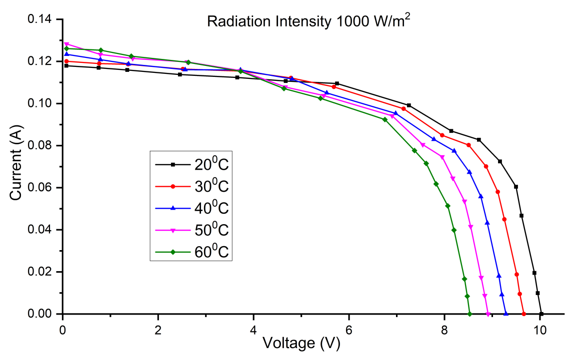

Figure 6.7 I-V Characteristics for p-Si PV Module

The basic equation for solar cells for short circuit current and open circuit voltage can be expressed as

$$I = I_L - I_0\left(e^{\frac{qV}{\eta KT}} - 1\right) \qquad (1)$$

$$V_{OC} = \frac{\eta KT}{q}\ln\left(\frac{I_L}{I_0}\right) \qquad (2)$$

Here, where k is the Boltzmann constant, T is the temperature in terms of Kelvin, q is the Electric charge, V is the output voltage of the solar cell, I_L is the light-generated current, and I_0 is the reverse saturation current. The above two equations show that the voltage of the cell reduces noticeably when its temperature increases. However, the increment of cell current due to temperature rise is negligible.

6.4 P-V Characteristics of Monocrystalline & Polycrystalline PV Modules

The power of a PV module can be expressed as P=VI, where, V is the voltage and I is the current. Fig 6.8, Fig-6.10, and Fig-6.12 shows the P-V characteristics of m-Si PV modules for solar radiation intensity 400, 600, and 1000 W/m^2 for temperature ranging from 20^{0}C to 60^{0}C. Fig 6.9, Fig-6.11, and Fig-6.13 shows the P-V curve for p-Si with the same variation. The power–voltage characteristics estimation follows the same trend as the current–voltage characteristics. From the graph it is observed that the power is increased almost linearly with increasing cell temperature, for the low voltage range, the power reached a maximum point, hence it is found that the power is decreased rapidly for the higher voltage range due to the increasing rate of generation of the photon with increasing cell temperature. Which revealed the rapid increment in the reverse saturation current as reported by [70]. The PV characteristics show that the maximum power point corresponding voltage is less than the open circuit voltage. Similarly, the corresponding current is also less than the short circuit current. The variation in current and voltage is almost identical for both types of PV modules for different cell temperatures. These results are similar to the earlier reported work [71-72].

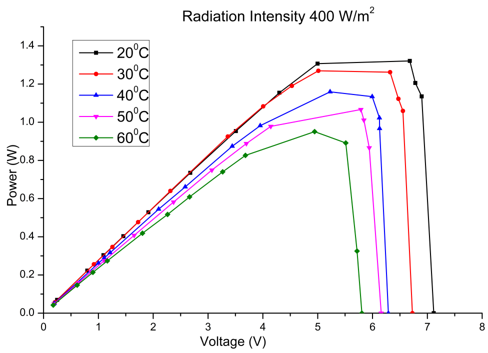

Figure 6.8 P-V Characteristics for m-Si PV Module

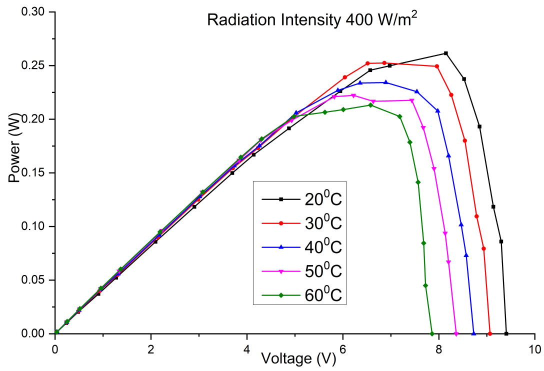

Figure 6.9 P-V Characteristics for p-Si PV Module

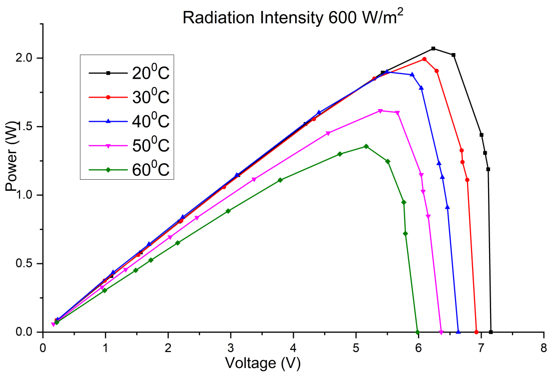

Figure 6.10 P-V Characteristics for m-Si PV Module

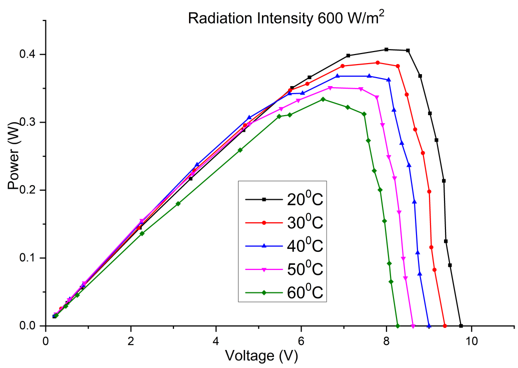

Figure 6.11 P-V Characteristics for p-Si PV Module

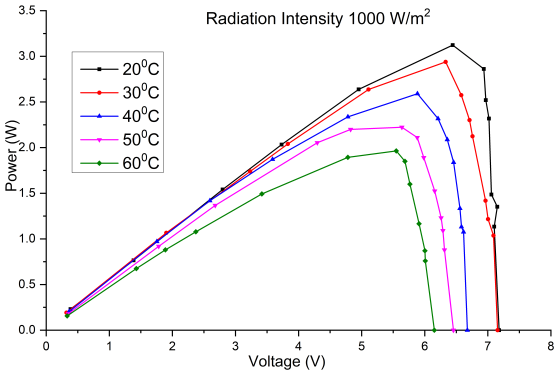

Figure 6.12 P-V Characteristics for m-Si PV Module

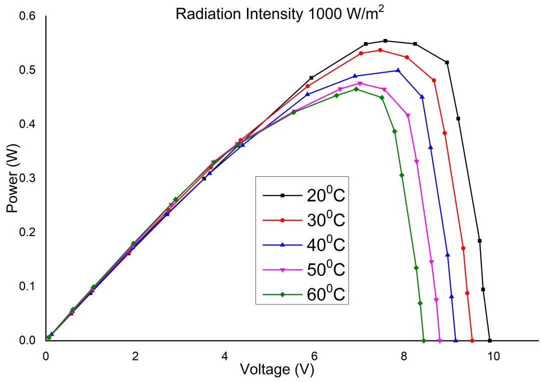

Figure 6.13 P-V Characteristics for p-Si PV Module

6.5 The efficiency of PV Modules

The efficiency of a PV module can be expressed as $\eta = \frac{I_{SC} V_{OC} FF}{P_{in}}$ Now, from the previous section we have already seen that with increasing the temperature for a fixed intensity the open circuit voltage and power decrease significantly, since the fill factor is linearly dependent on these two parameters, as a result, the efficiency will also decrease with increasing temperature.Fig-6.14 shows the variation of efficiency with temperature for 200 to 1000 W/m^2 for p-Si whereas fig-6.15 shows the variation of m-Si. For both modules, the efficiency decreased significantly with increasing temperature.

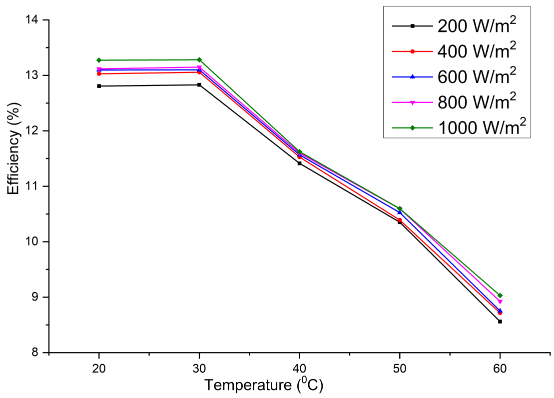

Figure 6.14 Variation of Efficiency with Temperature for m-Si PV Module

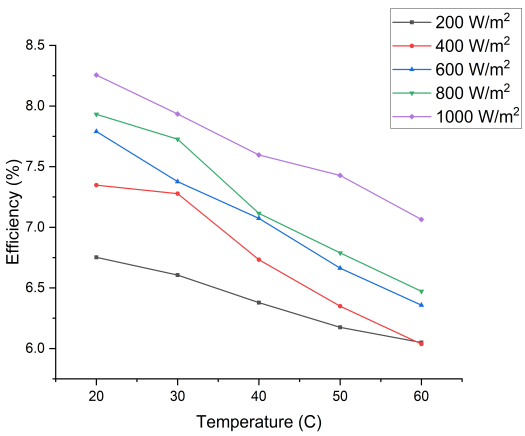

Figure 6.15 Variation of Efficiency with Temperature for p-Si PV Module

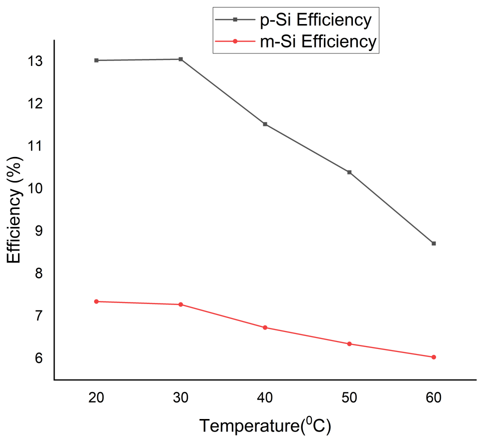

Figure 6.16 Comparison of Efficiency with Temperature for m-Si & p-Si PV Module

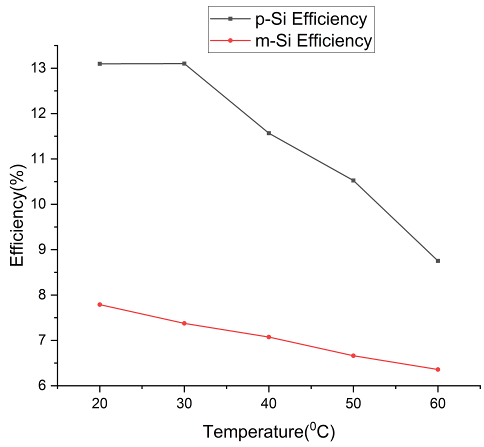

Figure 6.17 Comparison of Efficiency with Temperature for m-Si & p-Si PV Module

PV Module Type	**Temperature (^{0}C)**				
	20	**30**	**40**	**50**	**60**
m-Si	13.02874	13.05639	11.5256	10.39132	8.71515
p-Si	7.34793	7.27773	6.73277	6.34952	6.03684

Table 6.1 Efficiency Vs Temperature Table for m-Si PV module at 400 W/m^2

PV Module Type	**Temperature (^{0}C)**				
	20	**30**	**40**	**50**	**60**
m-Si	13.09591	13.10055	11.56672	10.52567	8.7517
p-Si	7.79008	7.376	7.074	6.66289	6.358

Table 6.2 Efficiency Vs Temperature Table for m-Si PV module at 600 W/m^2

Fig 6.16 shows the efficiency comparison between the p-Si and m-Si PV modules for 400 W/m^2 whereas Figure-6.17 shows the comparison for 600 W/m^2. Since we stated that the average solar radiation per day in India is roughly about 400-600 W/m^2 so, one can conclude that for the Indian subcontinent zone, m-Si will be always a better option than p-Si any day. One more thing can be said from the above two figures the rate of decrement of the panel's efficiency with respect to temperature is higher in m-Si compared to p-Si.

So, we can see that in every radiation and harsh temperature situation, the m-Si PV module gives better performance and efficiency than a p-Si module, but does that mean we will always use m-Si- PV modules, to check the economic feasibility we will now analyze the simulation result of these two types of PV panels obtained from the PVsyst software. Now, for installing a solar power plant the power output or the efficiency of the module has a big impact. But these two are not the only parameters that we need to look after some other parameters also, such as ROI, payback period, cost per energy production, and saved carbon emission. To achieve our goal we will now discuss these output parameters in detail. As per the economic report generated by PVsyst software for each city, a tabular form can be obtained as follows (Table-6.3)

Climatic Region	**City**	**Input Parameters**				**Output Parameters**			
		Panel Size	**Panel Type**	**Soiling Loss (%)**	**Annual Average Degradation (%)**	**Energy Production Cost (INR/kWh)**	**ROI (%)**	**Payback Period (Year)**	**Saved Carbon Emission (tCo_2)**
Tropical Wet & Dry	Kolkata	325Wp 27 V	Mono	1.5	0.4	1.764	198.8	8.9	153.8
					2.3	2.192	125.0	9.8	121.8
					4.2	2.684	69.7	11.2	97.6
		325Wp 30 V	Poly	1.5	0.5	1.691	216.5	8.3	158.3
					2	2.009	153.5	8.9	131.7
					3.5	2.364	103.4	9.7	110.4
		325Wp 27 V	Mono	3	0.4	1.788	193.9	9.0	151.5
					2.3	2.223	121.1	10.0	119.9
					4.2	2.721	66.5	11.5	96.1
		325Wp 30 V	Poly	3	0.5	1.714	211.3	8.4	156.0
					2	2.036	149.2	9.1	129.7
					3.5	2.397	99.7	9.9	108.7
		325Wp 27 V	Mono	5	0.4	1.822	187.3	9.2	148.5
					2.3	2.264	115.8	10.3	117.5
					4.2	2.772	62.3	11.9	94.1
		325Wp 30 V	Poly	5	0.5	1.746	204.4	8.6	152.9
					2	2.075	143.3	9.3	127.1
					3.5	2.442	94.8	10.2	106.4

Table 6.3 Simulation-Based Economic Analysis of Kolkata

In the above table, the four economic parameters are presented for different soiling loss and degradation loss percentages for both m-Si and p-Si PV modules in Kolkata. As we can see from the table due to so many input parameter variations it is very difficult to present these data in a graphical view so, for a more understandable and presentable view we assumed a mean intermediate value for soiling loss and degradation loss as 3% & 2% for both m-Si and p-Si PV modules respectively. Hence by keeping all the input parameter constant a simulation is obtained & from the result, a graphical comparison is made between two types of PV modules in each city for each climatic region. The techno-economic analysis details for all other cities are attached in Annexure-I.

6.6 Return on Investment

Return on Investment (ROI) is one of the parameters to measure profitability to evaluate how well an investment has performed throughout the lifetime of a project. ROI is calculated by dividing an investment's net profit (or loss) by its initial cost it is expressed in terms of percentage. A negative ROI indicates that the system is not profitable.[52]

$$ROI = \frac{\text{Net benefit at the end of the lifetime}}{\text{Total investment}}$$

Climatic Region	**City**	**ROI (%)**	
		p-Si	**m-Si**
The Himalayan Western	Leh	538.5	497.7
Montane	Kullu	141.9	124.5
Humid Subtropical	Bhopal	208.3	186.1
Arid	Jodhpur	229.0	206.1
Semi-Arid	New Delhi	479.5	440.5
Tropical Wet & Dry	Kolkata	149.2	131.2
Tropical Wet	Panaji	231.8	208.8
Sub Humid Continental	Dharwad	203.3	181.4
Tropical Oceanic	Digilpur	179.5	160

Table 6.4 Comparison of ROI for m-Si & p-Si PV Modules

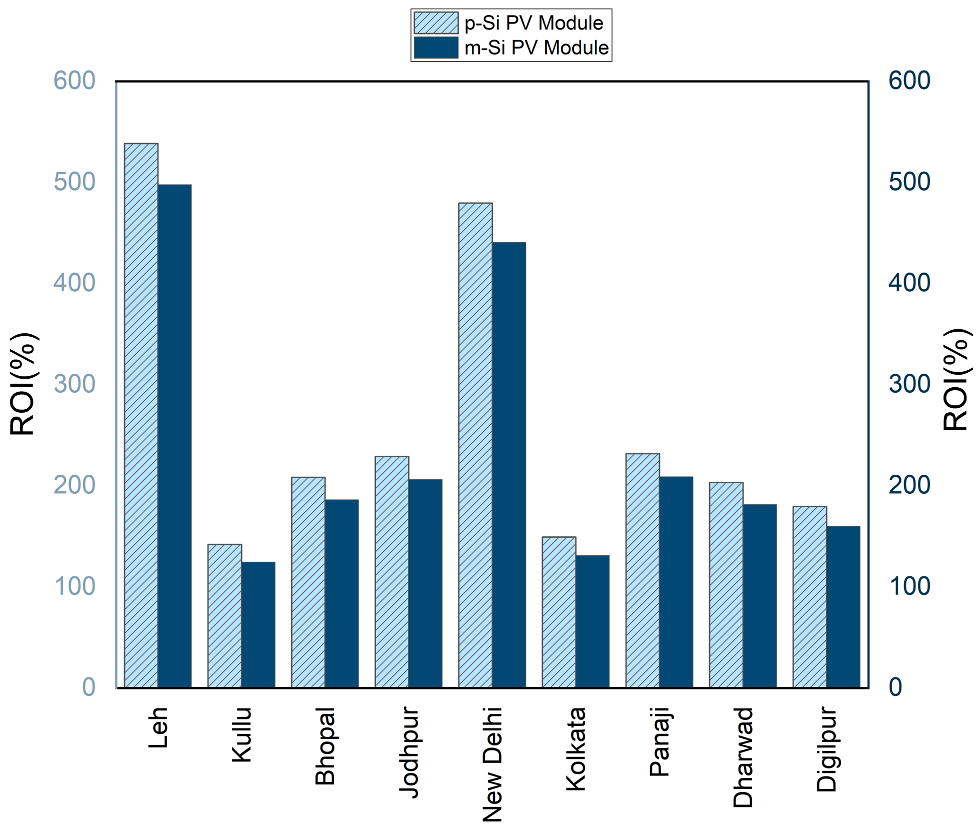

Figure 6.18 Comparison of ROI

Here in Table 6.4 for each city in the climatic zones of India ROI is calculated for both m-Si & p-Si PV modules for soiling loss of 3% and degradation loss of 2%. Here we can see that for Leh the ROI is highest whereas for Kullu the ROI is lowest, another noticeable thing is that despite having better efficiency in m-Si than p-Si the ROI is way better in p-Si compared to m-Si as shown in Figure-6.18. This is due to the fact that the module price is less for p-Si compared to m-Si.

6.7 Payback Period

The payback period is defined as the number of years required to recover the original investment. This means it is the period at the end of which the net investment made in the installation and operating costs section has produced sufficient net revenue to recover the costs. If the system is not profitable means more expenses than income, the payback period is undefined. The amount recovered each year is calculated by the formula

The recovered amount for the year = [Net balance of year + Self-consumption saving for year + Redemption part of the loan for the year]. The net balance of the year represents the after-tax profit minus possible dividend payments.[52]

Climatic Region	**City**	**Payback Period (Year)**	
		p-Si	**m-Si**
The Himalayan Western	Leh	3.5	3.7
Montane	Kullu	9.4	10.1
Humid Subtropical	Bhopal	7.3	7.9
Arid	Jodhpur	6.8	7.4
Semi-Arid	New Delhi	3.8	4.1
Tropical Wet & Dry	Kolkata	9.1	9.8
Tropical Wet	Panaji	6.7	7.3
Sub Humid Continental	Dharwad	7.4	8
Tropical Oceanic	Digilpur	8.1	8.7

Table 6.5 Comparison of Payback Periods for m-Si & p-Si PV Modules

Here from Table-6.5, we can see that for Leh the payback period is the lowest 3.5 years for p-Si and 3.7 years for m-Si whereas Kullu has the highest payback period which is 9.4 years for m-Si and 10.1 years for p-Si. Slight differences in the payback period for m-Si and p-Si PV modules are observed as shown in Figure-6.19.

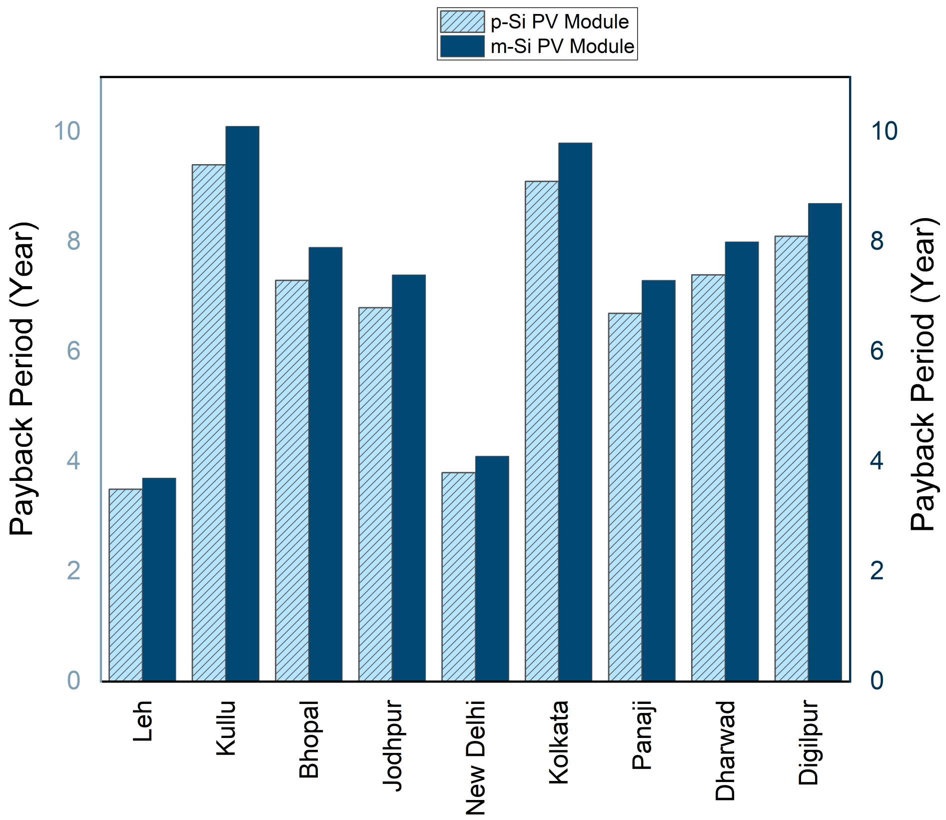

Figure 6.19 Comparison of Payback Period

6.8 Energy Production Cost

The average net present cost of electricity generation for a generator over its lifetime is defined as The levelized cost of electricity (LCOE) is a. It is one of the key parameters for investment. The Total yearly cost of the system is considered the sum of loan and running costs. The annual average value on project duration including the inflation rate if defined. The LCOE is the price of the produced kWh. It takes into account the present value of future cash flows by applying a Discount Rate.[52]

The formula used for LCOE calculation in Pvsyst is defined as

$$\text{LCOE} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

I_t = Investment and expenditures for the year (t)

M_t = Operational and maintenance expenditures for the year (t)

E_t = Electricity production for the year (t)

r = Discount rate that could be earned in alternative investments

n = Lifetime of the system

Climatic Region	City	Energy Production Cost (INR/kWh)	
		p-Si	m-Si
The Himalayan Western	Leh	1.738	1.831
Montane	Kullu	2.323	2.448
Humid Subtropical	Bhopal	2.096	2.221
Arid	Jodhpur	1.848	1.951
Semi-Arid	New Delhi	2.137	2.254
Tropical Wet & Dry	Kolkata	2.036	2.150
Tropical Wet	Panaji	2.244	2.366
Sub Humid Continental	Dharwad	2.095	2.210
Tropical Oceanic	Digilpur	2.540	2.667

Table 6.6 Comparison of LCOE for m-Si & p-Si PV Modules

From Table-6.6 we can see that the lowest production cost is in Leh whereas the highest production cost is in Digilpur. As shown in Figure-6.20 similar to the payback period minor variations are observed between two types of PV modules among the chosen cities.

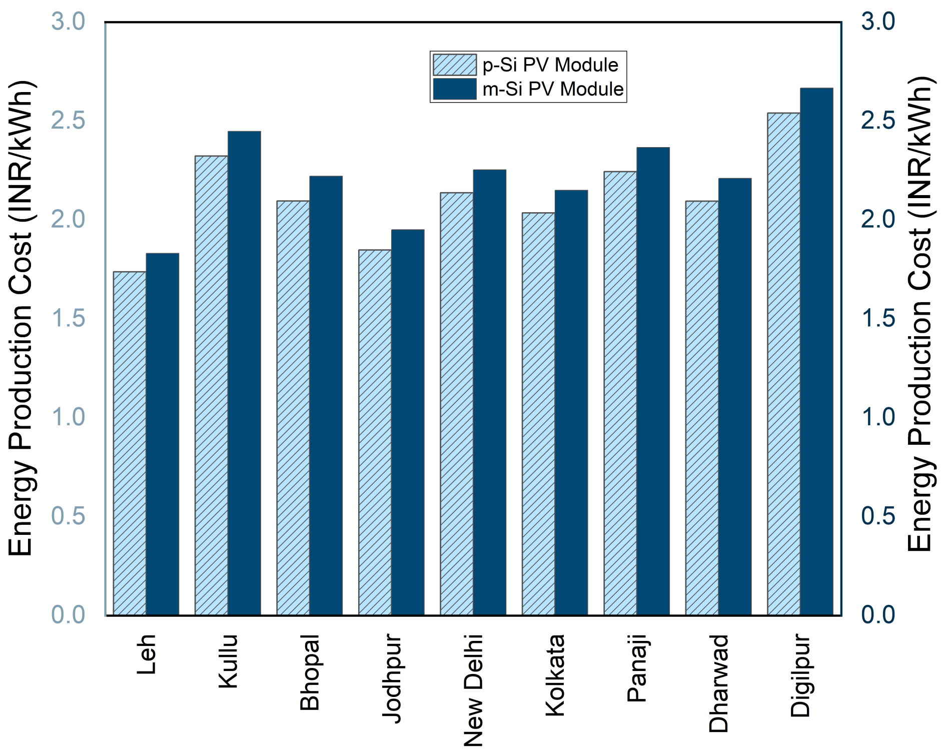

Figure 6.20 Comparison of Energy Production Cost

6.9 Saved Carbon Emission

The carbon balance is currently one of the deciding factors for the economic evaluation of a power plant. As we know the emitted carbon dioxide and carbon monoxide due to the combustion of fossil fuel from thermal power plants are the contributor to global warming. This allows us to estimate the saving in CO_2 emissions expected for the PV installation compared to a fossil fuel power plant[52]. The basis of this calculation is so-called Life Cycle Emissions (LCE), which represent the emissions of CO_2 associated with a given component or energy amount. These values include the total life cycle of a component or energy amount, including production, operation, maintenance, disposal, etc. The electricity produced by the PV installation will replace the same amount of electricity in the existing grid. If the carbon footprint of the solar PV installation per kWh is smaller compared to the grid electricity production, there will be a net saving of carbon dioxide emissions. So, the total carbon balance for a PV installation is the difference between produced and saved CO_2 Emissions.

Climatic Region	City	Saved Carbon Emission (tCo_2)	
		p-Si	**m-Si**
The Himalayan Western	Leh	180.5	173.2
Montane	Kullu	129.8	124.4
Humid Subtropical	Bhopal	137.4	131.7
Arid	Jodhpur	144.8	138.8
Semi-Arid	New Delhi	134.6	129.0
Tropical Wet & Dry	Kolkata	129.7	124.4
Tropical Wet	Panaji	132.5	127.0
Sub Humid Continental	Dharwad	138.8	133.1
Tropical Oceanic	Digilpur	120.7	115.7

Table 6.7 Comparison of Saved Carbon Emission for m-Si & p-Si PV Modules

Table-6.7 represents the comparison between the saved amount of carbon emission for m-Si and p-Si PV modules. As referred to in Figure-6.21 in Leh the saved carbon is the highest 180.5 tCO_2 for m-Si and 173.2 for p-Si and Digilpur is the lowest 120.7 tCO_2 for m-Si and 115.7 for p-Si. All the other cities lie in between them.

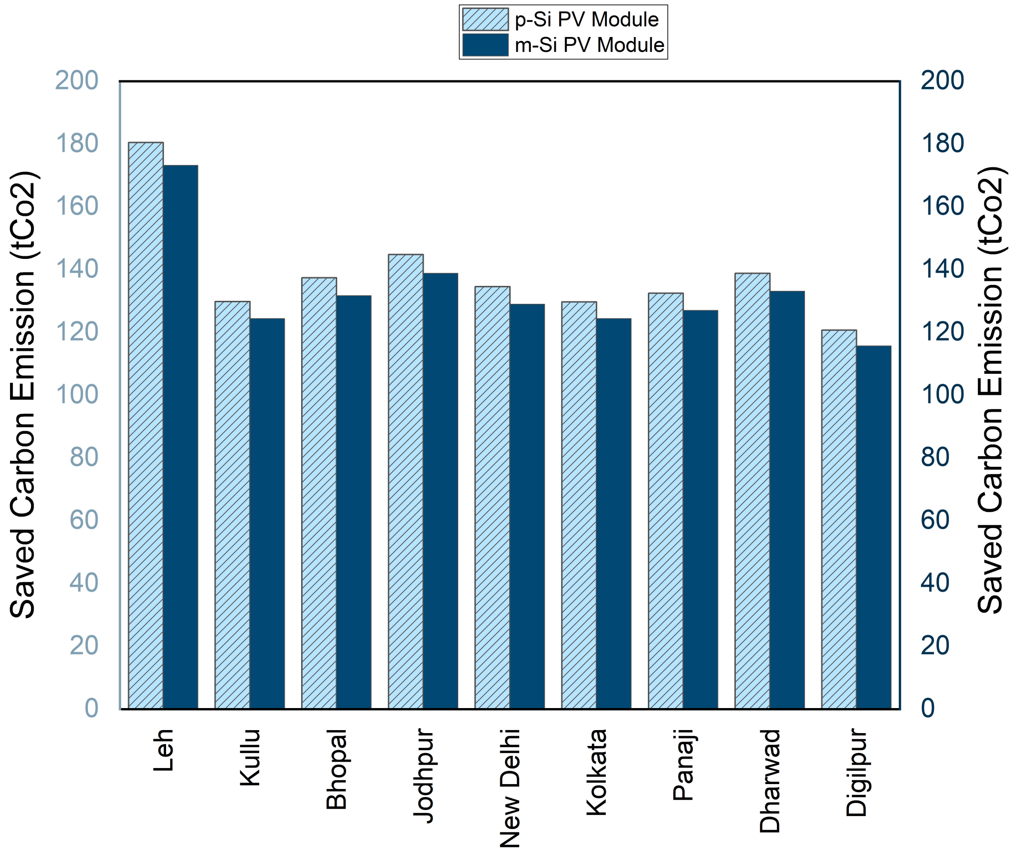

Figure 6.21 Comparison of Saved Carbon Emission

6.10 Conclusion

The chapter provides us a detailed tabular and graphical view of the study. The four main output parameters for installing a PV module as well as the I-V and P-V characteristics for both m-Si and p-Si are presented. For which city the parameters are highest and lowest are stated along with a probable explanation. The analysis of the data eventually helps to conclude this work which is stated in the next chapter.

Chapter-7

Conclusion & Avenues of Future Works

7.1 Conclusion

The journey started with the concept of energy and the world energy reserves and consumption scenario. Then the Indian energy scenario in terms of fossil fuels and renewable energy is presented and the importance of solar energy over other renewable energy sources is established, after that a summarized form of the objective of the current study is presented. Next in Chapter-2 along with the literature survey, the gap of knowledge, probable solution, and detailed steps of execution of the present work are reported. In Chapter-3 a brief overview of solar PV technology along with the working principle and characteristics are presented. In Chapter-4 the basic overview of PVsyst software is given. The experimental setups and methods of the study are described in Chapter-5. In this study, the effect of cell temperature on the m-Si solar and p-Si solar PV modules is observed. The results show that the cell temperature has a significant impact on photovoltaic cells and it controls the quality and performance of solar PV modules. The open circuit voltage (V_{oc}), output power (P), and cell efficiency (η) are found to be decreased with cell temperature for both m-Si solar cells and p-Si, while the short circuit current is observed to be increased slightly with increasing cell temperature for m-Si cells whereas decreases for p-Si PV modules. The rate of decrement of efficiency with respect to temperature is higher in m-Si PV Modules than p-Si PV modules. The result shows good agreement with the available literature. So, based on performance any day m-Si will be always better compared to p-Si. Now to check the economic feasibility of the power plant a techno-economic analysis has been performed using PVsyst software with obtained data. The four main output parameters such as unit energy production cost, ROI, Saved Carbon emission, and payback period are calculated for each chosen city in each climatic zones in India. For a presentable view, a constant soiling loss and degradation loss for all chosen cities has been considered and the simulation is performed. The result shows that despite having better efficiency than the p-Si PV module in every output parameter m-Si module failed miserably. For Leh the ROI is highest 538.5% for p-Si and 497.7% for m-Si, whereas for Kullu the ROI is lowest 141.1% for p-Si and 124.4% for m-Si. In Leh the saved carbon emission is the highest 180.5 tCO_2 for m-Si and 173.2 tCO2 for p-Si and lowest in Digilpur 120.7 tCO_2 for m-Si and 115.7 tCO2 for p-Si. In terms of ROI and saved carbon emission there is a significant difference between p-Si and m-Si. The payback period in Leh is the lowest 3.5 years for p-Si and 3.7 years for m-Si whereas Kullu has the highest payback period which is 9.4 years for m-Si and 10.1 years for p-Si. The LCOE in Leh is lowest 1.738 INR/kWh for p-Si and 1.831 INR/kWh for m-Si whereas for Digilpur the LCOE is highest 2.540 INR/kWh for p-Si and 2.667 INR/kWh for m-Si. In terms of payback period and unit energy production cost, both of the modules are almost the same but p-Si shows a slightly better performance compared to m-Si. The main objective of the study was to identify the most suitable type of PV module for a specific climatic zone in India. Through the study, we can conclude that if a module shows a better performance in high-temperature and harsh climatic conditions that doesn't ensure that we will consider it for installing a solar PV Power plant. For installing a solar PV power plant despite efficiency there are a few other important parameters that we need to encounter. According to the simulation it has been found that in terms of long-term profit and smoother production rate p-Si PV module is a more suitable option in the Indian subcontinent compared to m-Si whereas, in terms of efficiency and total power, m-Si will be a better option, other than that since for a same sized m-Si PV module required less surface area compared to a p-Si PV module [73] so if there is a land constraint, m-Si PV module can be a better option. Among the chosen city the most suitable city for installing a PV plant is Leh, followed by Dharwad and Jodhpur. For a more accurate study, there are a few issues that we need to solve are discussed in the next section.

7.2 Avenues of Future Works

For simulation-based economic analysis, we used a range of soiling loss and degradation loss percentage values whereas both these two parameters are heavily dependent on the environmental conditions of the location which can only be obtained from live data unfortunately no such recorded data or literature have been found for each location for the simulation study. So, a further study can be done on each location by recording live data throughout the lifetime of a module which will give more accurate results.

With the obtained datasets an optimization mathematical model can be produced which will take input as meteorological data and gives output as ROI, Payback period, etc further, it can be validated with live recorded data which will eventually meet our objective to predict a suitable PV module for a specific location within no time more efficiently.

The above comparison can be performed by using other PV module technologies such as CIGS, CdTe, HIT,a-Si, Thin film, etc. and a generalized optimization model can be obtained.

Annexure-I

Climatic Region	City	Input Parameters				Output Parameters			
		Panel Size	Panel Type	Soiling Loss (%)	Annual Average Degradation (%)	Energy Production Cost (INR/kWh)	ROI (%)	Payback Period (Year)	Saved Carbon Emission (tCo_2)
Tropical Oceanic	Diglipur	325 Wp 28 V	Mono	1.5	0.4	2.196	235.3	7.9	141.3
					2.3	2.729	153.3	8.7	113.3
					4.2	3.341	91.9	9.7	90.7
		325 Wp 30 V	Poly	1.5	0.5	2.108	254.2	7.4	147.5
					2	2.505	184.4	7.9	122.6
					3.5	2.948	128.8	8.5	102.7
		325 Wp 28 V	Mono	3	0.4	2.226	229.8	8.1	141.0
					2.3	2.767	148.9	8.8	111.6
					4.2	3.388	88.4	9.9	89.3
		325 Wp 30 V	Poly	3	0.5	2.138	248.3	7.6	145.3
					2	2.540	179.5	8.1	120.7
					3.5	2.999	124.7	8.7	101.1
		325 Wp 28 V	Mono	5	0.4	2.269	222.3	8.2	138.1
					2.3	2.820	143.0	9.0	109.2
					4.2	3.452	83.6	10.2	87.4
		325 Wp 30 V	Poly	5	0.5	2.178	240.5	7.7	142.3
					2	2.588	173.0	8.3	118.3
					3.5	3.046	119.2	8.9	99.0

Table 8.1 Simulation-Based Economic Analysis of Diglipur

Climatic Region	City	Input Parameters				Output Parameters			
		Panel Size	Panel Type	Soiling Loss (%)	Annual Average Degradation (%)	Energy Production Cost (INR/kWh)	ROI (%)	Payback Period (Year)	Saved Carbon Emission (tCo_2)
The Himalayan Western	Leh	325 Wp 28 V	Mono	1.5	0.4	1.397	663.7	3.5	213.6
					2.3	1.736	496.7	3.6	170.2
					4.2	2.126	371.7	3.7	137.4
		325 Wp 30 V	Poly	1.5	0.5	1.444	689.5	3.4	219.0
					2	1.715	547.7	3.4	183.0
					3.5	2.019	435.0	3.5	154.2
		325 Wp 28 V	Mono	3	0.4	1.519	641.4	3.6	210.6
					2.3	1.888	476.6	3.7	167.7
					4.2	2.311	353.2	3.8	135.4
		325 Wp 30 V	Poly	3	0.5	1.463	678.4	3.4	216.0
					2	1.738	538.5	3.5	180.5
					3.5	2.045	427.2	3.6	152.1
		325 Wp 28 V	Mono	5	0.4	1.551	624.6	3.7	205.9
					2.3	1.928	463.2	3.8	164.0
					4.2	2.360	342.4	3.9	132.3
		325 Wp 30 V	Poly	5	0.5	1.489	663.3	3.5	212.0
					2	1.769	525.9	3.5	177.1
					3.5	2.082	416.6	3.6	149.1

Table 8.2 Simulation-Based Economic Analysis of Leh

Climatic Region	City	Input Parameters				Output Parameters			
		Panel Size	Panel Type	Soiling Loss (%)	Annual Average Degradation (%)	Energy Production Cost (INR/kWh)	ROI (%)	Payback Period (Year)	Saved Carbon Emission (tCo_2)
Tropical Wet	Goa	325 Wp 28 V	Mono	1.5	0.4	1.941	296.0	6.7	156.9
					2.3	2.413	200.7	7.2	124.4
					4.2	2.954	129.4	7.9	99.8
		325 Wp 30 V	Poly	1.5	0.5	1.863	318.6	6.3	161.5
					2	2.214	237.4	6.6	134.5
					3.5	2.605	172.8	7.0	112.9
		325 Wp 28 V	Mono	3	0.4	1.968	289.7	6.8	154.6
					2.3	2.446	195.7	7.4	122.5
					4.2	2.994	125.3	8.0	98.3
		325 Wp 30 V	Poly	3	0.5	1.889	312.0	6.4	159.2
					2	2.244	231.8	6.7	132.5
					3.5	2.641	168.1	7.2	111.2
		325 Wp 28 V	Mono	5	0.4	2.005	281.2	7.0	151.5
					2.3	2.492	188.9	7.5	120.1
					4.2	3.050	119.9	8.2	96.3
		325 Wp 30 V	Poly	5	0.5	1.924	303.0	6.6	156.0
					2	2.286	224.3	6.9	129.8
					3.5	2.691	161.8	7.3	108.9

Table 8.3 Simulation-Based Economic Analysis of Panaji

Climatic Region	City	Input Parameters				Output Parameters			
		Panel Size	Panel Type	Soiling Loss (%)	Annual Average Degradation (%)	Energy Production Cost (INR/kWh)	ROI (%)	Payback Period (Year)	Saved Carbon Emission (tCo_2)
Sub Humid Continental	Dharwad	325 Wp 28 V	Mono	1.5	0.4	1.814	263.1	7.3	164.2
					2.3	2.254	173.9	8.0	130.3
					4.2	2.760	107.1	8.8	104.7
		325 Wp 30 V	Poly	1.5	0.5	1.740	284.7	6.9	169.1
					2	2.067	208.5	7.3	140.9
					3.5	2.433	147.9	7.8	118.3
		325 Wp 28 V	Mono	3	0.4	1.838	257.2	7.5	161.8
					2.3	2.285	169.2	8.1	128.4
					4.2	2.797	103.3	9.0	103.1
		325 Wp 30 V	Poly	3	0.5	1.763	278.5	7.0	166.7
					2	2.095	203.3	7.4	138.8
					3.5	2.466	143.5	7.9	116.5
		325 Wp 28 V	Mono	5	0.4	1.873	249.3	7.3	158.7
					2.3	2.328	162.9	8.3	125.8
					4.2	2.850	98.2	9.2	101.0
		325 Wp 30 V	Poly	5	0.5	1.796	270.1	7.1	163.4
					2	2.134	196.3	7.6	136.1
					3.5	2.512	137.6	8.1	114.2

Table 8.4 Simulation-Based Economic Analysis of Dharwad

Climatic Region	City	Input Parameters				Output Parameters			
		Panel Size	Panel Type	Soiling Loss (%)	Annual Average Degradation (%)	Energy Production Cost (INR/kWh)	ROI (%)	Payback Period (Year)	Saved Carbon Emission (tCo_2)
Humid Subtropical	Bhopal	325 Wp 28 V	Mono	1.5	0.4	1.815	269.1	7.2	162.6
					2.3	2.255	178.4	7.8	129.0
					4.2	2.761	110.5	8.6	103.6
		325 Wp 30 V	Poly	1.5	0.5	1.741	291.0	6.8	167.4
					2	2.068	213.6	7.1	139.5
					3.5	2.434	152.0	7.6	117.1
		325 Wp 28 V	Mono	3	0.4	1.839	263.1	7.3	160.3
					2.3	2.286	173.6	8.0	127.1
					4.2	2.799	106.6	8.8	102.1
		325 Wp 30 V	Poly	3	0.5	1.765	284.7	6.9	165.0
					2	2.096	208.3	7.3	137.4
					3.5	2.467	147.5	7.8	115.3
		325 Wp 28 V	Mono	5	0.4	1.873	255.0	7.5	157.1
					2.3	2.329	167.2	8.2	124.6
					4.2	2.851	101.5	9.0	100.0
		325 Wp 30 V	Poly	5	0.5	1.797	276.2	7.0	161.8
					2	2.136	201.2	7.4	134.7
					3.5	2.513	141.5	8.0	113.0

Table 8.5 Simulation-Based Economic Analysis of Bhopal

Climatic Region	City	Input Parameters				Output Parameters			
		Panel Size	Panel Type	Soiling Loss (%)	Annual Average Degradation (%)	Energy Production Cost (INR/kWh)	ROI (%)	Payback Period (Year)	Saved Carbon Emission (tCo_2)
Arid	Jodhpur	325 Wp 28 V	Mono	1.5	0.4	1.601	290.7	6.8	171.3
					2.3	1.990	198.2	7.3	135.9
					4.2	2.436	129.0	8.0	109.2
		325 Wp 30 V	Poly	1.5	0.5	1.534	313.3	6.4	176.4
					2	1.823	234.4	6.7	146.9
					3.5	2.034	191.0	7.0	123.4
		325 Wp 28 V	Mono	3	0.4	1.622	284.6	6.9	168.9
					2.3	2.017	193.4	7.4	133.9
					4.2	2.469	125.1	8.1	107.6
		325 Wp 30 V	Poly	3	0.5	1.555	306.9	6.5	173.8
					2	1.848	229.0	6.8	144.8
					3.5	2.175	167.1	7.2	121.5
		325 Wp 28 V	Mono	5	0.4	1.653	276.4	7.1	165.6
					2.3	2.054	186.9	7.6	131.3
					4.2	2.515	119.8	8.3	105.4
		325 Wp 30 V	Poly	5	0.5	1.584	298.2	6.6	170.4
					2	1.882	221.8	7.0	141.9
					3.5	2.215	161.0	7.4	119.1

Table 8.6 Simulation-Based Economic Analysis of Jodhpur

Climatic Region	City	Input Parameters				Output Parameters			
		Panel Size	Panel Type	Soiling Loss (%)	Annual Average Degradation (%)	Energy Production Cost (INR/kWh)	ROI (%)	Payback Period (Year)	Saved Carbon Emission (tCo_2)
Montane	Kullu	325 Wp 28 V	Mono	1.5	0.4	2.009	192.1	9.1	153.7
					2.3	2.497	118.4	10.1	121.8
					4.2	3.056	63.1	11.7	97.7
		325 Wp 30 V	Poly	1.5	0.5	1.928	209.1	8.5	158.3
					2	2.291	146.3	9.2	131.8
					3.5	2.696	96.3	10.1	110.5
		325 Wp 28 V	Mono	3	0.4	2.075	180.5	9.5	148.4
					2.3	2.531	114.4	10.3	120.0
					4.2	3.099	59.9	12.0	96.2
		325 Wp 30 V	Poly	3	0.5	1.955	203.9	8.7	156.0
					2	2.323	141.9	9.4	129.8
					3.5	2.733	92.6	10.3	108.8
		325 Wp 28 V	Mono	5	0.4	2.075	180.5	9.5	148.4
					2.3	2.580	109.1	10.6	117.5
					4.2	3.158	55.6	12.4	94.2
		325 Wp 30 V	Poly	5	0.5	1.992	196.9	8.9	152.8
					2	2.367	136.0	9.6	127.2
					3.5	2.785	87.7	10.6	106.6

Table 8.7 Simulation-Based Economic Analysis of Kullu

Climatic Region	City	Input Parameters				Output Parameters			
		Panel Size	Panel Type	Soiling Loss (%)	Annual Average Degradation (%)	Energy Production Cost (INR/kWh)	ROI (%)	Payback Period (Year)	Saved Carbon Emission (tCo_2)
Semi-Arid	New Delhi	325 Wp 28 V	Mono	1.5	0.4	1.849	581.8	3.9	159.4
					2.3	2.298	427.5	4.1	126.4
					4.2	2.814	312.0	4.2	101.5
		325 Wp 30 V	Poly	1.5	0.5	1.774	620.3	3.7	164.0
					2	2.108	488.6	3.8	136.6
					3.5	2.481	383.8	3.9	114.6
		325 Wp 28 V	Mono	3	0.4	1.875	571.5	4.0	157.0
					2.3	2.330	419.3	4.1	124.5
					4.2	2.853	305.3	4.3	99.9
		325 Wp 30 V	Poly	3	0.5	1.779	609.4	3.7	161.6
					2	2.137	479.5	3.8	134.6
					3.5	2.516	376.1	3.9	112.9
		325 Wp 28 V	Mono	5	0.4	1.910	557.6	4.1	153.9
					2.3	2.374	408.2	4.2	121.9
					4.2	2.907	296.4	4.4	97.8
		325 Wp 30 V	Poly	5	0.5	1.833	594.7	3.8	158.4
					2	2.178	467.2	3.9	131.8
					3.5	2.563	365.8	4.0	110.6

Table 8.8 Simulation-Based Economic Analysis of New Delhi

Climatic Region	City	Month	Average GHI (W/m^2)	Average DHI (W/m^2)	Average Temperature (^0C)	Average Relative Humidity (%)	Average Wind Speed (m/s)
Arid	Jodhpur	January	175.5143	91.73727	16.2556	30.86168	1.836111
		February	208.7445	91.65741	19.71731	26.68206	2.032044
		March	257.1425	91.625	25.29395	23.64261	2.055824
		April	289.5718	95.89815	31.74468	20.91436	2.657917
		May	296.5797	97.56944	34.47065	27.36633	3.024462
		June	275.763	97.2581	35.07681	43.51654	3.959583
		July	216.3669	90.72454	31.53472	65.34734	3.532079
		August	203.3799	90.01389	29.28378	74.59577	2.976703
		September	224.7917	91.27662	28.99606	66.22546	2.190093
		October	223.2003	91.60185	27.38145	40.77815	1.552016
		November	181.106	96.22569	22.32505	38.79071	1.701852
		December	168.664	97.07523	16.23714	36.34609	1.871819

Table 8.9 Meteorological Data for Jodhpur 2017-2019

Climatic Region	City	Month	Average GHI (W/m^2)	Average DHI (W/m^2)	Average Temperature (^0C)	Average Relative Humidity (%)	Average Wind Speed (m/s)
The Himalayan Western	Leh	January	114.039	45.81944	-11.9746	44.69984	2.063657
		February	156.9206	60.69742	-10.0688	47.70609	2.081134
		March	230.8504	83.18593	-6.21478	46.84281	2.020139
		April	265.4449	109.2375	2.038102	43.44068	2.138194
		May	301.4297	139.5049	5.818056	41.91384	2.215856
		June	319.6866	133.7005	10.10579	41.02808	2.194792
		July	296.0004	123.4059	15.27796	42.01952	2.035764
		August	285.4758	99.02778	14.85627	41.20611	1.877199
		September	258.3319	61.61852	9.996343	36.74999	1.824306
		October	217.5995	49.05556	3.098522	33.25136	1.891435
		November	145.5833	44.79583	-5.74162	42.08762	1.996296
		December	122.1496	31.27464	-12.7561	45.02098	2.019907

Table 8.10 Meteorological Data for Leh 2017-2019

Climatic Region	City	Month	Average GHI (W/m^2)	Average DHI (W/m^2)	Average Temperature (^{0}C)	Average Relative Humidity (%)	Average Wind Speed (m/s)
Montane	Kullu	January	108.4606	43.39919	4.156855	51.02751	1.346102
		February	139.1007	60.68105	6.103423	52.12473	1.504514
		March	189.772	73.84901	9.424462	51.81826	1.591443
		April	236.7269	95.65324	16.11519	51.13515	1.813009
		May	252.0542	108.9785	19.25959	53.09242	1.916711
		June	233.9264	109.9838	22.08944	53.31038	2.006852
		July	182.0157	114.8392	22.29315	52.58488	1.974597
		August	189.3898	104.4082	21.56913	52.20189	1.678629
		September	200.9611	75.47963	19.37963	51.49866	1.414074
		October	210.7791	51.74686	14.67406	51.08081	1.399821
		November	128.9921	45.8713	10.15394	53.27869	1.302037
		December	129.2097	34.50045	5.598118	56.00356	1.369579

Table 8.11 Meteorological Data for Kullu 2017-2019

Climatic Region	City	Month	Average GHI (W/m^2)	Average DHI (W/m^2)	Average Temperature (^{0}C)	Average Relative Humidity (%)	Average Wind Speed (m/s)
Humid Subtropical	Bhopal	January	198.3114	56.71953	17.68177	32.32273	2.259954
		February	221.7961	68.95635	21.60451	29.94491	2.277199
		March	265.3082	82.46729	26.27115	22.67203	2.242014
		April	298.6741	92.68704	31.99162	18.65775	2.351042
		May	298.5739	107.2854	35.41299	20.87246	2.423495
		June	236.7509	123.3431	32.65361	52.38627	2.365394
		July	143.5004	99.96371	26.67012	86.13763	2.299306
		August	137.8136	101.3763	25.42325	92.3265	2.378935
		September	165.2875	93.29907	25.02963	89.4178	2.326273
		October	210.5067	75.47043	23.80372	72.51754	2.197338
		November	193.0542	70.9338	20.89569	61.30037	2.212153
		December	172.6022	63.50403	17.14104	51.96286	2.319676

Table 8.12 Meteorological Data for Bhopal 2017-2019

Climatic Region	City	Month	Average GHI (W/m^2)	Average DHI (W/m^2)	Average Temperature (^{0}C)	Average Relative Humidity (%)	Average Wind Speed (m/s)
Sub Humid Continental	Dharwad	January	232.4467	65.22133	22.18082	41.32175	2.614583
		February	263.1979	65.3125	24.90982	33.95421	2.569676
		March	283.6277	80.19758	27.55932	40.41328	2.612153
		April	282.0227	95.66296	29.80088	47.2389	2.655903
		May	263.578	109.1456	28.74915	61.02602	2.71875
		June	194.7204	122.8481	24.95644	84.16551	2.550116
		July	167.0972	119.6886	23.49704	90.54962	2.498727
		August	175.5547	121.8082	23.14794	90.96961	2.527315
		September	201.1014	108.3667	23.25995	89.33329	2.48588
		October	192.1595	101.2706	23.27321	84.4863	2.481481
		November	211.4588	74.27824	22.14824	74.6167	2.476505
		December	205.5874	68.73029	21.64498	66.76643	2.543403

Table 8.13 Meteorological Data for Dharwad 2017-2019

Climatic Region	City	Month	Average GHI (W/m^2)	Average DHI (W/m^2)	Average Temperature (^{0}C)	Average Relative Humidity (%)	Average Wind Speed (m/s)
Semi-Arid	New Delhi	January	143.3069	62.63486	13.46438	42.7309	1.764468
		February	179.0382	75.23462	17.36245	40.59775	1.712037
		March	237.0063	88.93056	23.37236	31.32983	1.765856
		April	275.2338	113.7861	31.13472	24.35271	1.858449
		May	274.4377	131.5677	34.98159	22.978	1.795023
		June	263.4282	139.5532	36.12444	36.62694	1.837731
		July	202.3194	129.0237	32.15309	65.9697	1.722454
		August	197.0341	118.2106	29.91967	76.74555	1.698958
		September	194.9213	97.39028	28.3088	72.845	1.91794
		October	204.5484	91.1017	25.04722	52.85582	1.907407
		November	150.3565	75.45787	19.95227	48.7195	1.902778
		December	133.8401	58.02336	13.88351	47.50456	1.927431

Table 8.14 Meteorological Data for New Delhi 2017-2019

Climatic Region	City	Month	Average GHI (W/m^2)	Average DHI (W/m^2)	Average Temperature (^0C)	Average Relative Humidity (%)	Average Wind Speed (m/s)
Tropical Wet	Panaji	January	226.4409	69.39695	26.63907	57.65377	3.156597
		February	253.7798	69.81994	27.65729	58.14625	3.106713
		March	274.6035	90.5681	28.22585	64.83646	3.187153
		April	280.7134	107.5153	29.60213	68.68429	3.343056
		May	256.0399	120.6438	29.60367	74.84182	3.430208
		June	156.7	110.0523	28.37231	86.10326	3.351505
		July	140.3553	110.4996	27.19906	90.45905	3.364468
		August	157.8405	116.3221	26.73925	90.77703	3.39919
		September	192.7792	98.85185	26.91417	88.21329	3.334954
		October	194.8253	93.12007	27.64247	82.5966	3.331597
		November	215.7532	70.99769	27.27671	73.7475	3.330093
		December	203.2737	67.96237	26.84915	67.71405	3.347338

Table 8.15 Meteorological Data for Panaji 2017-2019

Climatic Region	City	Month	Average GHI (W/m^2)	Average DHI (W/m^2)	Average Temperature (^0C)	Average Relative Humidity (%)	Average Wind Speed (m/s)
Tropical Oceanic	Diglipur	January	182.3329	80.16039	26.81846	78.87202	4.221181
		February	250.813	78.68155	26.78309	74.15756	4.037384
		March	278.5641	90.52778	27.52988	73.65974	4.049306
		April	258.0551	106.1491	29.27181	75.04602	4.416088
		May	192.8831	111.7769	29.57684	80.80666	4.715509
		June	162.2394	111.0801	28.94255	85.55381	4.691898
		July	155.7832	108.8262	28.50381	87.12436	4.668866
		August	143.754	103.7236	28.12039	88.27166	4.328356
		September	182.0301	106.9819	28.03542	85.88135	4.098032
		October	198.0506	101.0918	28.40143	82.96878	4.293171
		November	196.4509	83.88519	28.36741	80.53119	4.217361
		December	185.1559	73.6241	27.42509	78.7894	4.03206

Table 8.16 Meteorological Data for Digilpur 2017-2019

References

[1] Nayan, Md Faysal, and S. M. Safayet Ullah. "Modelling of solar cell characteristics considering the effect ofelectrical and environmental parameters." *Green Energy and Technology (ICGET), 2015 3rd International Conference on*. IEEE, 2015.

[2] https://s3.ap-south 1 amazonaws.com/aipnpc.org/downloads/T_5053 _GENERAL_ASPECTS OF_ENERGY_MANAGEMENT_AND_ENERGY_AUDIT.pdf

[3]https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2021-full-report.pdf

[4] https://ourworldindata.org/energy-mix

[5] https://www.mospi.gov.in/publication/energy-statistics-india-2023

[6]https://www.un.org/development/desa/pd/sites/www.un.org.development.desa.pd/files/undesa_pd_2023_policy-brief-153.pdf

[7] Panwar, N. L., Kaushik, S. C., & Kothari, S. (2011). Role of renewable energy sources in environmental protection: A review. *Renewable and sustainable energy reviews*, *15*(3), 1513-1524.

[8] https://www.iea.org/reports/global-energy-review-co2-emissions-in-2021-2

[9] https://mnre.gov.in/img/documents/uploads/file_f-1671012052530.pdf

[10] Pillai, I. R., & Banerjee, R. (2009). Renewable energy in India: Status and potential. *Energy*, *34*(8), 970-980.

[11] Usage Areas of Energy, 2014, http://enerjisistemleri.blogspot.com.tr/2010/12/resim-galerisi.html

[12] Carr, A. J., & Pryor, T. L. (2004). A comparison of the performance of different PV module types in temperate climates. *Solar energy*, *76*(1-3), 285-294.

[13] Abdelkader, M. R., Al-Salaymeh, A., Al-Hamamre, Z., & Sharaf, F. (2010). A comparative Analysis of the Performance of Monocrystalline and Multiycrystalline PV Cells in Semi Arid Climate Conditions: the Case of Jordan. *Jordan Journal of Mechanical & Industrial Engineering*, *4*(5).

[14] Ghazali, A. M., & Rahman, A. M. A. (2012). The performance of three different solar panels for solar electricity applying solar tracking device under the Malaysian climate condition. *Energy and environment Research*, *2*(1), 235.

[15] El-din, A. H., Gabra, C. F., & Ali, A. H. (2014, March). A comparative analysis between the performances of monocrystalline, polycrystalline and amorphous thin film in different temperatures at different locations in Egypt. In *1 st Africa Photovoltaic Solar Energy Conference and Exhibition, Durban*

[16] Başoğlu, M. E., Kazdaloğlu, A., Erfidan, T., Bilgin, M. Z., & Çakır, B. (2015). Performance

analyzes of different photovoltaic module technologies under İzmit, Kocaeli climatic conditions. *Renewable and Sustainable Energy Reviews*, *52*, 357-365

[17] Magare, D. B., Sastry, O. S., Gupta, R., Betts, T. R., Gottschalg, R., Kumar, A., ... & Singh, Y. K. (2016). Effect of seasonal spectral variations on performance of three different photovoltaic technologies in India. *International Journal of Energy and Environmental Engineering*, *7*(1), 93-103.

[18] Taşçıoğlu, A., Taşkın, O., & Vardar, A. (2016). A power case study for monocrystalline and polycrystalline solar panels in Bursa City, Turkey. *International Journal of Photoenergy*, *2016*.

[19] Nayan, M. F., Ullah, S. S., & Saif, S. N. (2016, September). Comparative analysis of PV module efficiency for different types of silicon materials considering the effects of environmental parameters. In *2016 3rd International Conference on Electrical Engineering and Information Communication Technology (ICEEICT)* (pp. 1-6). IEEE.

[20] Romero-Fiances, I., Muñoz-Cerón, E., Espinoza-Paredes, R., Nofuentes, G., & De la Casa, J. (2019). Analysis of the performance of various pv module technologies in Peru. *Energies*, *12*(1), 186.

[21] *Abubakar Ohinoyi Musa, Adamu Bala Isah Comparative Study of Monocrystalline and Polycrystalline Silicon Solar Modules in Kebbi State Environmen International Journal Of Scientific & Engineering Research,Volume10, Issue9,September-2019*

[22] Hidayanti, F. (2020). The effect of monocrystalline and polycrystalline material structure on solar cell performance. *International Journal*, *8*(7).

[23] Ayadi, O., Shadid, R., Bani-Abdullah, A., Alrbai, M., Abu-Mualla, M., & Balah, N. (2022). Experimental comparison between Monocrystalline, Polycrystalline, and Thin-film solar systems under sunny climatic conditions. *Energy Reports*, *8*, 218-230.

[24] Kadia, N. J., Hashim, E. T., & Abdullah, O. I. (2022). PERFORMANCE OF DIFFERENT PHOTOVOLTAIC TECHNOLOGIES FOR A-SI (A-SI) AND COPPER INDIUM GALLIUM DI-SELENIDE (CIGS) PHOTOVOLTAIC MODULES. *Journal of Engineering and Sustainable Development*, *26*(1), 95-105.

[25] Mulcué-Nieto, L. F., Echeverry-Cardona, L. F., Restrepo-Franco, A. M., García-Gutiérrez, G. A., Jiménez-García, F. N., & Mora-López, L. (2020). Energy performance assessment of monocrystalline and polycrystalline photovoltaic modules in the tropical mountain climate: The case for Manizales-Colombia. *Energy Reports*, *6*, 2828-2835.

[26] Adouane, M., Al-Qattan, A., Alabdulrazzaq, B., & Fakhraldeen, A. (2020). Comparative performance evaluation of different photovoltaic modules technologies under Kuwait harsh climatic conditions. *Energy reports*, *6*, 2689-2696.

[27] Taraba, M., Adamec, J., Danko, M., Drgona, P., & Urica, T. (2019). Properties measurement of the thin film solar panels under adverse weather conditions. *Transportation Research Procedia*, *40*, 535-540.

[28] Elibol, E., Özmen, Ö. T., Tutkun, N., & Köysal, O. (2017). Outdoor performance analysis of different PV panel types. *Renewable and Sustainable Energy Reviews*, *67*, 651-661.
[29] Attari, K., Elyaakoubi, A., & Asselman, A. (2016). Performance analysis and investigation of a grid-connected photovoltaic installation in Morocco. *Energy Reports*, *2*, 261-266.
[30] Lim, M. S. W., He, D., Tiong, J. S. M., Hanson, S., Yang, T. C. K., Tiong, T. J., ... & Chong, S. (2022). Experimental, economic and life cycle assessments of recycling end-of-life monocrystalline silicon photovoltaic modules. *Journal of Cleaner Production*, *340*, 130796.
[31] Mirzaei, M., & Mohiabadi, M. Z. (2017). A comparative analysis of long-term field test of monocrystalline and polycrystalline PV power generation in semi-arid climate conditions. *Energy for Sustainable Development*, *38*, 93-101.
[32] Louzazni, M., Khouya, A., & Mosalam, H. (2020). Comparison of power production for different photovoltaic technologies in Nile Delta, Egypt. *Procedia Manufacturing*, *46*, 724-729.
[33] Karin, T., Jones, C. B., & Jain, A. (2019, June). Photovoltaic degradation climate zones. In *2019 IEEE 46th Photovoltaic Specialists Conference (PVSC)* (pp. 0687-0694). IEEE.
[34] Ozden, T. (2022). A countrywide analysis of 27 solar power plants installed at different climates. *Scientific Reports*, *12*(1), 746.
[35] Yadav, S., & Bajpai, U. (2017). Variation in the performance of solar photovoltaic power plant due to climatic parameters in composite climatic zone. *IJETER*, *5*, 67-72.
[36] Gopi, A., Sudhakar, K., Keng, N. W., Krishnan, A. R., & Priya, S. S. (2021). Performance modeling of the weather impact on a utility-scale PV power plant in a tropical region. *International Journal of Photoenergy*, *2021*, 1-10.
[37] Mussard, M., & Amara, M. (2018). Performance of solar photovoltaic modules under arid climatic conditions: A review. *Solar Energy*, *174*, 409-421.
[38] Seddik, Z. B., Taher, M. B., Laknizi, A., Ahachad, M., Bahraoui, F., & Mahdaoui, M. (2022). Hybridization of Taguchi method and genetic algorithm to optimize a PVT in different Moroccan climatic zones. *Energy*, *250*, 123802.
[39] Suhail, M., Akhtar, I., & Kirmani, S. (2021). Economic analysis of 26 kW solar powered system for a commercial building in India. *Materials Today: Proceedings*, *46*, 10892-10895.
[40] Yazdani, H., & Yaghoubi, M. (2021). Techno-economic study of photovoltaic systems performance in Shiraz, Iran. *Renewable Energy*, *172*, 251-262.
[41] Chandel, M., Agrawal, G. D., Mathur, S., & Mathur, A. (2014). Techno-economic analysis of solar photovoltaic power plant for garment zone of Jaipur city. *Case Studies in Thermal Engineering*, *2*, 1-7.
[42] Ahsan, S., Javed, K., Rana, A. S., & Zeeshan, M. (2016). Design and cost analysis of 1 kW photovoltaic system based on actual performance in Indian scenario. *Perspectives in Science*, *8*, 642-644.
[43] Poudyal, R., Loskot, P., & Parajuli, R. (2021). Techno-economic feasibility analysis of a 3-

kW PV system installation in Nepal. *Renewables: Wind, Water, and Solar*, *8*(1), 1-18.
[44] Kumar, N. M., Gupta, R. P., Mathew, M., Jayakumar, A., & Singh, N. K. (2019). Performance, energy loss, and degradation prediction of roof-integrated crystalline solar PV system installed in Northern India. *Case Studies in Thermal Engineering*, *13*, 100409.
[45] Louzazni, M., Khouya, A., & Mosalam, H. (2020). Comparison of power production for different photovoltaic technologies in Nile Delta, Egypt. *Procedia Manufacturing*, *46*, 724-729.
[46] https://www.smithsonianmag.com/sponsored/brief-history-solar-panels-180972006/
[47] https://energyeducation.ca/encyclopedia/Photovoltaic_effect
[48] https://www.cleanenergyreviews.info/blog/solar-panel-components-construction
[49] Bayod-Rújula, A. A. (2019). Solar photovoltaics (PV). In *Solar Hydrogen Production* (pp. 237-295). Academic Press.
[50] https://encyclopedia.pub/entry/26456
[51] https://www.uprm.edu/aret/docs/Ch_5_PV_systems.pdf
[52] https://www.pvsyst.com/help/index.html?contents_table.htm
[53] https://cs.mcgill.ca/~rwest/wikispeedia/wpcd/wp/g/Geography_of_India.htm
[54] https://geoportal.natmo.gov.in/map.php?id=1
[55] https://jercjkl.nic.in/pdf/Sou_Moto_Petition_FY_2022-205-08-2022.pdf
[56] https://hperc.org/new1/File1/dosolar2-2023.pdf
[57] https://mperc.in/Final%20Tariff%20Order%20for%20FY%202021-22_30_06_21.pdf
[58] https://egramswaraj.gov.in/resources/urja/documents/conceptNoteGramUrjaSwaraj.pdf
[59] https://cercind.gov.in/2015/orders/SO17N.pdf
[60] https://wberc.gov.in/sites/default/files/Discussion%20Paper%20with%20Notice.pdf
[61] http://jercuts.gov.in/writereaddata/UploadFile/JERC%20RE%20Generic%20Tariff_1159.pdf
[62] https://kerc.karnataka.gov.in/uploads/media_to_upload1675839453.pdf
[63] https://mnre.gov.in/img/documents/uploads/file_f-1629353920466.pdf
[64] https://nsrdb.nrel.gov/data-viewer
[65] Maghami, M. R., Hizam, H., Gomes, C., Radzi, M. A., Rezadad, M. I., & Hajighorbani, S. (2016). Power loss due to soiling on solar panel: A review. *Renewable and Sustainable Energy Reviews*, *59*, 1307-1316.
[66] Rajput, P., Tiwari, G. N., Sastry, O. S., Bora, B., & Sharma, V. (2016). Degradation of mono-crystalline photovoltaic modules after 22 years of outdoor exposure in the composite climate of India. *Solar Energy*, *135*, 786-795.
[67] Singh, S. K., & Chander, N. (2022). Mid-life degradation evaluation of polycrystalline Si solar photovoltaic modules in a 100 kWp grid-tied system in east-central India. *Renewable Energy*, *199*, 351-367.
[68] https://solargis.com/maps-and-gis-data/download/india
[69] Jamil, B., Siddiqui, A. T., & Akhtar, N. (2016). Estimation of solar radiation and optimum tilt

angles for south-facing surfaces in Humid Subtropical Climatic Region of India. *Engineering Science and Technology, an International Journal*, *19*(4), 1826-1835.

[70] Arjyadhara, P., Ali, S.M., Chitralekha, J., 2013. Analysis of solar PV cell performance with changing irradiance and temperature. Int. J. Eng. Comput. Sci. 2 (1), 214–220.

[71] Fesharaki, V.J., Dehghani, M., Fesharaki, J.J., 2011. The effect of temperature on photovoltaic cell efficiency. In: Proceedings of the 1st International Conference on Emerging Trends in Energy Conservation- ETEC, Tehran, Iran, November 20–22

[72] Sabry, M., Ghitas, A.E., 2008. Influence of temperature on methods for determining Silicon solar cell series resistance. J. Sol. Energy Eng. 129, 331–335.

[73] https://www.solarsquare.in/blog/monocrystalline-vs-polycrystalline-solar-panels/