EXPERIMENTAL STUDY ON THE PERFORMANCE OF SOLAR PV SYSTEMS INTEGRATED WITH AGROPHOTOVOLTAICS

Thesis Submitted for the Award of the Degree of

DOCTOR OF PHILOSOPHY

in

Mechanical Engineering

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2023

CERTIFICATE

This is to certify that the work reported in the Ph. D. thesis entitled ***“Experimental Study on the Performance of Solar PV Systems Integrated with Agrophotovoltaics”*** submitted in fulfillment of the requirement for the reward of degree of **Doctor of Philosophy (Ph.D.)** in the Department of Mechanical Engineering, is a research work carried out by **Waghmare Rahul Marotrao, 41800887**, is bonafide record of his original work carried out under my supervision and that no part of thesis has been submitted for any other degree, diploma or equivalent course.

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DECLARATION

I, hereby declared that the presented work in the thesis entitled ***"Experimental Study on the Performance of Solar PV Systems Integrated with Agrophotovoltaics"*** in fulfilment of degree of **Doctor of Philosophy (Ph. D.)** is outcome of research work carried out by me under the supervision of **Dr. Ravindra Jilte**, working as **Professor**, in the **School of Mechanical Engineering,** Lovely Professional University, Punjab, India and under the co-supervision of **Dr. Sandeep Joshi**, working as **Assistant Professor** in **Department of Mechanical Engineering**, Shri Ramdeobaba College of Engineering and Management, Nagpur, Maharashtra, India. In keeping with general practice of reporting scientific observations, due acknowledgements have been made whenever work described here has been based on findings of other investigator. This work has not been submitted in part or full to any other University or Institute for the award of any degree.

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ABSTRACT

As the rate of globalization increasing, there has been an alarming increase in energy demand. The natural resources that are driving globalization have a limited growth, are static for some or even diminishing for others. The conventional energy sources are incapable of keeping up with the exponential energy demand. Consequently, it is essential to utilize the non-conventional energy sources to their fullest extent.

One of those sources which is regarded as the origin of all sources is solar energy. Solar PV technology is considered as one of the best technologies for solar to electrical energy conversion. However, due to limited efficiency of the solar energy conversion technology, it requires huge land to convert it to electricity. Since there is limited amount of land on planet, it may soon be difficult to find the suitable land for installation of solar electrical conversion system. In future, one of the options left could be to use agricultural land for the installation of solar PV systems. A severe land energy conflict would then begin because the agricultural land would not be able to produce enough food to feed the human civilization in the near future.

To address this challenge, combining solar PV and agriculture on same piece of land can be a viable solution; these systems are known as Agrophotovoltaics systems or Agrivoltaic systems (APV). Agrophotovoltaics (APV) is the coexistence of solar photovoltaics (PV) and agriculture on the same piece of land. Although the concept of APV is known for the last two decades, its actual penetration in society is inconsiderable; this is the real motivation for the present research work.

Besides, the efficiency of the solar PV system is limited, among several other parameters it depends on its operating temperature. Most of the solar cell materials, respond to the limited portion of the terrestrial solar spectrum (in most of the cases, visible and near infrared spectrum). The solar cell responds to the photons which have energy equal to the band gap energy of solar cell material. The photon with higher energy than the band gap of solar cell causes the thermal losses in the cell and reduces its electrical output.

Thus, it is always desirable to keep the low operating temperature of the solar cells. To address this issue, different techniques have been proposed by many investigators in the past. Many of these studies include combined photovoltaic thermal systems (PVT), where the PV module is expose to the entire solar spectrum, and heat from the PV module is extracted by means of circulating air or liquids. Heat extraction improves the electrical performance of the

PV module. The focus of this study is to investigate the use of APV system to reduce the PV module temperature.

The present Research work focuses on the investigations on Agrophotovoltaic system and its benefit for cooling of solar PV systems for improved electrical yield.

Along with techno economic analysis, the Agrophotovoltaic Systems are currently being investigated for inherent thermal management of solar Photovoltaic modules using natural transpiration cooling by the crops. The present work aims at the development and performance analysis of 2kWp Agrophotovoltaic systems with different crop for various operating conditions such as different module heights and seasons.

For the experimental studies a 2 kWp solar Agrivoltaic system was designed and developed. The experimental work has been carried out at Nagpur [21° 08' N, 46.72'' E] India.

Three different crops Aloe vera, Tomato and Spinach were used for APV plant. The effect of different crops & their different heights on the performance of the power plant was investigated.

In the first phase, the Aloe barbadensis miller crops, also known as 'Aloe Vera,' were grown beneath the solar PV modules in half of the power plant, with the other half serving as a reference as a conventional power plant. The electrical and thermal performance of the conventional solar PV plant and the Agrivoltaic plant were compared for the two different heights I and II of the modules. The overall growth of Aloe Vera crops was also monitored throughout the experiments. The experiments show that, in comparison to a conventional solar PV system, the Agrivoltaic system's solar PV modules' temperature decreases by about 11.13% for height-I, while it decreases by about 12.75% for height-II, and its power output increases by 7.71% for height-I, and 7.12% for height-II per day. It was also noticed that the growth of the crop cultivated in the Agrivoltaic was comparable to that of the crop grown in the open sky. According to current experimental research, a 1MW Agrivoltaic system would generate 175200 kWh more electricity than a standard solar PV plant for height-I and 172200 kWh more electricity for height-II for the selected crop. In addition to the added benefit of increased power generation, the same plot of land would be used to other high-yielding crops.

In the second phase the Solanum Lycopersicum plants, also known as 'Tomato,' were grown beneath the solar PV modules in half of the power plant, with the other half serving as a reference as a conventional power plant. The electrical and thermal performance of the conventional solar PV plant and the Agrivoltaic plant were compared for the two different heights I and II of the modules. The overall growth of Tomato crops was also monitored throughout the experiments. The results of the experiments show that, in comparison to a conventional solar PV system, the agrivoltaic system's solar PV modules' temperature decreases by about 13.06% for height-I, while it decreases by about 12.38% for height-II, and its power output increases by 8.04% for height-I, and 6.75% for height-II per day. It was also noticed that the growth of the crop grown in the Agrivoltaic was comparable to that of the crop grown in the open sky. According to current experimental research, a 1MW Agrivoltaic system would generate 187500 kWh more electricity than a standard solar PV plant for height-I and 184500 kWh more electricity for height-II. In addition to the added benefit of increased power generation, the same plot of land would be used to grow other high-yielding crops.

In the third phase the Spinacia oleracea plants, also known as 'Spinach,' were grown beneath the solar PV modules in half of the power plant, with the other half serving as a reference as a conventional power plant. The electrical and thermal performance of the conventional solar PV plant and the Agrivoltaic plant were compared for the two different heights I and II of the modules. The overall growth of Spinach crops was also monitored throughout the experiments. The results of the experiments show that, in comparison to a conventional solar PV system, the agrivoltaic system's solar PV modules' temperature decreases by about 12.31% for height-I, while it decreases by about 11.77% for height-II, and its power output increases by 7.43% for height-I, and 6.55% more for height-II per day. It was also noticed that the growth of the crop grown in the Agrivoltaic was comparable to that of the crop grown in the open sky. According to current experimental research, a 1MW Agrivoltaic system would generate 169200 kWh more electricity than a standard solar PV plant for height-I and 122963 kWh more electricity for height-II. In addition to the added benefit of increased power generation, the same plot of land would be used to grow other high-yielding crops.

A theoretical estimation model is being developed in order to build a framework for simulating the performance of the agrivoltaic system for any specific location. The model consists of systematic methodology to predict the performance of MW scale APV plant by considering the location of plant. The model is based on the estimation of solar energy at the location, estimation of PV module temperature by the method of Multilinear Regression analysis, estimation of PV output.

The study concludes that the APV system has a potential to significantly reduce the possibility of future land -energy conflict. The experimental studies and predictive model formed in the present investigation will certainly be helpful for the future development of APV systems.

Acknowledgements

First, I feel great pleasure in acknowledging my deepest gratitude to my revered guide and mentor **Dr. Ravindra D. Jilte**, Professor, Mechanical Engineering Department, Lovely Professional University, Punjab, India, under whose guidance, motivation, and vigilant supervision I succeeded in completing my work. He infused the enthusiasm to continue this work into me.

I also take this opportunity to express a deep sense of gratitude to **Dr. Sandeep Joshi**, Assistant Professor, Department of Mechanical Engineering, Shri Ramdeobaba College of Engineering and Management, Nagpur, Maharashtra for his cordial support while designing the experimental setup, valuable information and guidance during experimental and theoretical studies which helped me in completing this task through various stages.

Also, my sincere thanks to all the faculty members and non-teaching staff of the School of Mechanical Engineering, Lovely Professional University, Punjab for availing me all the necessary facilities and co-operation for this work.

I thank the Almighty, the father of all, whose blessings have enabled me to accomplish my research work successfully. Words cannot express how grateful I am to my mother for all of the sacrifices that she has made on my behalf. A special thanks to my wife Ashwini for her encouragement during my studies. Not to forget my lovely Son and Daughter who has been my constant driving force for completing this work. I dedicate this research work to my father, Shri. Marotrao S. Waghmare, and my mother, Smt. Laxmi Waghmare, who have been greatly inspiring me in every endeavor of my life.

*I am obliged to **staff members of Mechanical Engineering Department JIT Nagpur** for their cooperation during the period of my assignment.*

At last, I wish to express my heartiest thanks to my friends for their support, love, and inspiration.

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Nomenclatures

Abbreviations

APV	Agrophotovoltaic
W-APV	Without Agrophotovoltaic
ACDB	Alternating Current Distribution Box
DCDB	Direct Current Distribution Box
PV	Photovoltaics
H_b	Monthly average of daily beam radiations on the horizontal surface (kW-hr/m^2 day)
H_d	Monthly average of daily diffused radiations on the horizontal surface (kW- hr/ m^2 day)
Hg	Monthly average of daily global radiations on the horizontal surface (kW-hr/ m^2 day)
Ho	Monthly average of daily extraterrestrial radiations on the horizontal surface (kW- hr/m^2 day)
I_b	Monthly average hourly beam radiations(W/m^2)
I_d	Monthly average hourly diffused radiations (W/m_2)
I_g (W/m^2)	Monthly average of hourly global radiations on the horizontal surface
IR	Infrared
Isc	Short circuit current (Amp)
I_{SC}	Solar constant (1367 W/m^2)
I_t	Incident flux falling on the tilted surface (W/m^2)
r_b	Tilt factor for the beam radiations
r_d	Tilt factor for diffused radiations
r_r	Tilt factor for the reflected radiations
STC	Standard Test Condition

CHAPTER-1

INTRODUCTION

This chapter emphasizes the need for renewable energy. The limitations of conventional solar PV system and the potential land use conflict in near future. The chapter also highlight the concept of APV system and their benefits. The chapter concludes at the overview of the present research work.

1.1. Global Energy Scenario and Need of Renewable Energy

Conventional energy sources are obviously insufficient to meet the continuously rising energy needs of modern civilization. The need for energy is expanding rapidly, and the available energy sources are running out at an even faster rate. Furthermore, the use of fossil fuels is a serious contributor to both global warming and climate change. Utilizing renewable energy sources to their fullest potential is therefore imperative. The most abundant, affordable and environmentally friendly source of renewable energy is considered to be the sun, which is the ultimate source of energy. [1]. The enormous amount of energy produced by the nuclear fusion reaction in the core of the sun as electromagnetic waves, which travel a large distance through the sun's atmosphere, vacuum and then various layers of atmosphere before arriving on Earth as terrestrial solar radiation. The energy of these terrestrial solar radiations is a thousand times more than the need of human civilization [2].

1.2. Terrestrial solar spectrum

The earth receives solar energy in the form of electromagnetic radiations from the sun. The solar radiations coming to the earth's surface are not monochromatic. Terrestrial solar radiations consist of ultraviolet (UV) radiations (150–380 nm), 48% visual (VIS) radiations (380–720 nm) and 43% infrared (IR) radiations (720–2500 nm) [3].

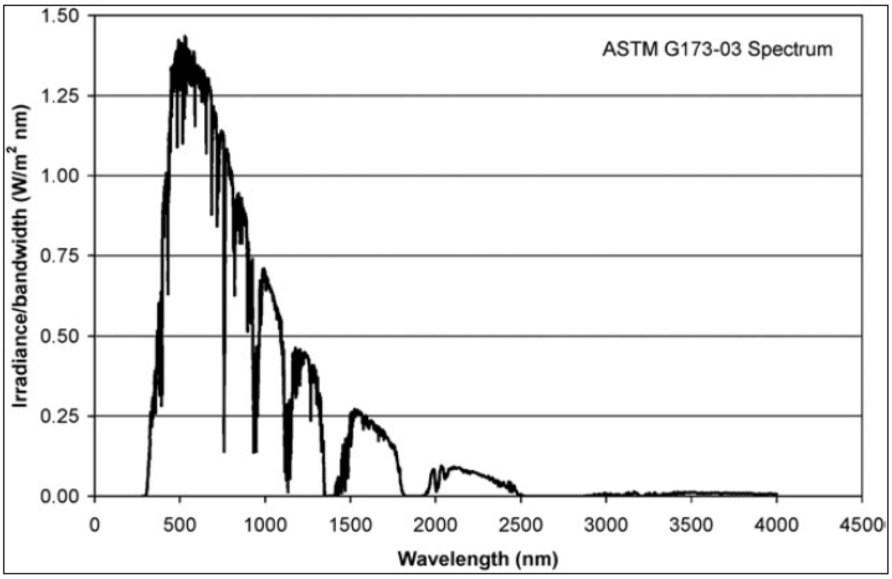


Fig. 1.1 The ASTM G173-03 terrestrial solar spectrum [3]

The terrestrial solar radiations have two components viz; direct radiations or beam radiations (in line with the sun) and the diffused radiations (scattered in the atmosphere). The total radiations (Direct + diffused) are known as global radiations. The photovoltaic devices mostly use the visible (VIS) and ultraviolet (UV) part of the solar spectrum. Whereas, the infrared part of the spectrum is used for solar thermal applications.

1.3. Solar Energy and Applications

Solar Energy is considered as origin of all the energy sources on earth. It is being used for several applications since long. The solar thermal energy conversions include solar water heating, solar cooking, solar thermal power generation, solar distillation systems. On the other hand the most popular application of Solar energy is its conversion to electricity using the solar Photovoltaic Technology.

Solar Photovoltaic technology uses solar PV modules which are made up of several solar cells connected together to convert the solar radiations into electricity. The electricity thus produced can be directly supplied to the grid using grid tied inverters or can be stored in the batteries for off sunshine applications. The solar photovoltaic techniques are being used for small scale applications like solar lanterns to a large-scale solar PV power plant of MW capacity.

1.4. Solar Photovoltaics

The devices used in the solar photovoltaic conversion are called solar cells. These devices convert the incoming solar radiations into DC electricity by the photovoltaic effect. Alexander-Edmond Becquerel made the discovery of the photovoltaic effect in 1839. [4]. The solar cells are made up of semiconductor materials like Silicon, Cadmium Telluride, and Gallium Arsenide. The first solar cell using Si-Pn junction is built by Russell Ohl in 1939 [5]. The Silicon is a commonly used semiconductor material for the commercial use solar cell. The following steps are involved in the working of solar cell.

I. Creation of pairs of positive and negative charges (Electron-hole pairs)
II. Separation of the positive and negative charges by potential gradient within the cell. (Charge separation)

The terrestrial solar radiations consist of photons of different energies. The photon Energy (E) is related to their wavelength by the relation

$$\text{Energy Photon(E)} = \frac{h\ x\ C}{\lambda} \qquad 1.1$$

Where, h: Plank's constant (6.62 X 10^{-34}J-S)

C: Velocity of light (3 X10^{8} m/s)

Substituting these values in eq. (1.1) gives

$$\text{Photon Energy (E)} = \frac{1.24}{\lambda}$$

Where (E) is in electron-volts and (λ) is in µm.

The terrestrial solar spectrum is not monochromatic thus the incoming photons possess different energies. Corresponding to 0.25 to 2.5 µm wavelength of incoming solar radiations the terrestrial photons have energy 0.49 to 4.9 eV. In the semiconductor materials, the electrons occupy one of the two energy bands, the valance band and the conduction band. The valence band has electron at a low energy level and is fully occupied. And the conduction band has electrons at a higher energy level and it is not fully occupied. The difference between the minimum energy of the electron in conduction band the maximum energy of electron in valence band is called band gap energy (Eg). The sunlight having energy (E) greater than the band gap of the material (Eg) is absorbed in the material and excites some of the electrons. The excess energy (E-Eg) is lost as heat. The exited electrons jump from the valence band to conduction band leaving behind the holes in the valence band. Thus, electron hole pairs are created. The electrons and the holes are mobile. They can be made to flow through the circuit if potential gradient exists within the cell. In case of silicon solar cells, the potential gradient is obtained by making the cell as a sandwich of two types of silicon P type and N type. Silicon of P type is doped with some trivalent atoms like Boron while, the N type is doped with pentavalent atoms like Phosphorous. The N type silicon has excess electron and P type has excess holes. When these two materials are joined together (P-N Junction) the excess electron from N type diffuse to recombine with the holes in P type and vice versa. As a result, the N type material becomes positively charged and P type becomes negatively charged. This creates a built-in potential at the junction as shown in Fig.1.2. The consequent electric field is adequate to separate the electron and holes (executing step-2) and causes direct electric current flow in the external load.

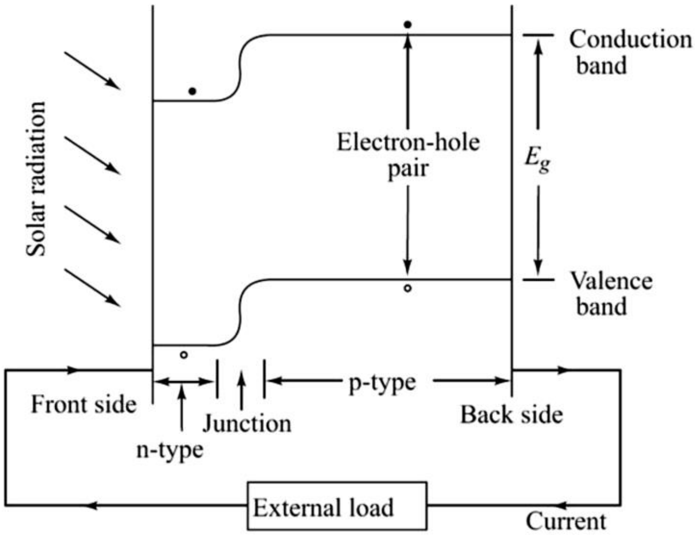


Fig. 1.2: Working principle of solar cell [2]

The typical cross section of single junction silicon solar cell is shown in fig.1.3. In general, the N type silicon is at the top side and the P type silicon forms the base of the solar cell. The metal electrode finger on the front side and metal electrode on the back side forms positive and negative terminals. Such several solar cells are attached in series to form a solar photovoltaic (PV) module used for all practical applications.

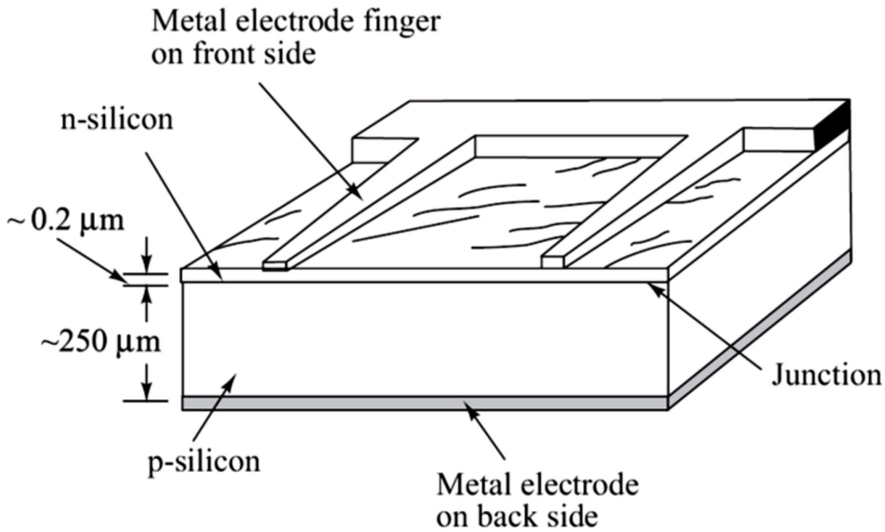


Fig. 1.3: Cross section of Si- Solar cell [2]

1.5. Land Requirement for PV power plant

In general, the commercial solar PV plant have either monocrystalline or polycrystalline silicon solar PV modules. The modules are to be installed at optimum tilt angle and most have adequate height/ground clearance for air circulation. Also, while installing a large number of PV modules the ground clearance and interrow spacings are to be chosen in such a way that the shade on the rows should not fall on another adjacent rows of the PV modules. Fig 1.4 shows the typical layout of the PV plant installations. Thus, the land requirement for PV plant can be calculated by considering the type of PV modules, elevation and interrow spacing. Considering as these factors the total land required for a 1 MW of solar PV power plant will be about 4 acres. [12]

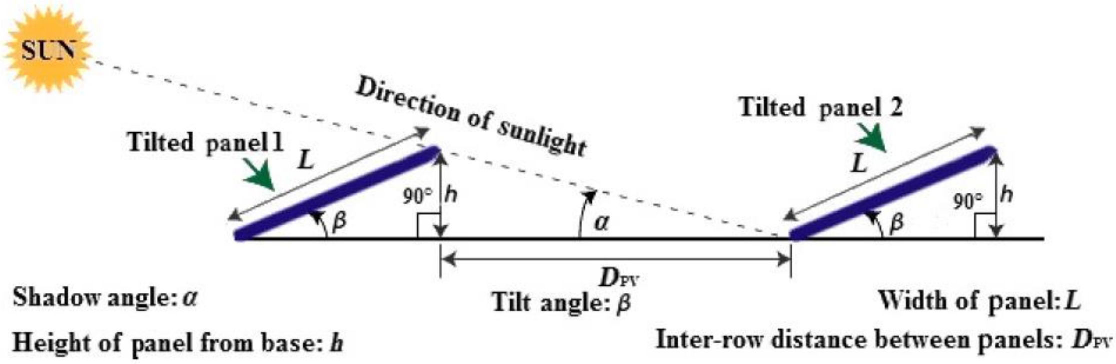


Fig. 1.4 Inter-row spacing of photovoltaic array. [12]

1.6. Parameters Affecting the Performance of the PV power plant

There are several parameters which affect the performance of solar cell and in turn PV module. The significant parameters are the intensity of incoming solar radiation, optical losses by reflection, and operating temperature of the solar cell. Some of the primarily influenced factors are as follows:

1.6.1.Solar Radiation Flux

The intensity of solar radiation affects the efficiency of PV modules majorly. More the solar radiations more the output of PV modules. For the maximum solar radiations, it is essential to orient the PV modules such that the radiations should face perpendicular to PV modules. Solar tracing systems are needed to alter the angles on which the modules are tilted to maximize the solar energy on the surface. That's because of the dependence of irradiance on the orientation and tilt angle of the PV module. The major drawback is that the installation and maintenance cost increases with the energy consumed during tracking. Besides, it also requires the installation area adding to its list of limitation. Thus, it is advantageous to change the inclination and till angle strenuously in a less frequently. In the northern hemisphere for the best azimuth position, generally PV modules are oriented facing the equator, but the optimal till angle varies according to geographic position, atmospheric condition and operation period of time using latitude information and exploiting falling solar radiation on a sloping PV module surface. [2]

1.6.2.Type of Solar Material

Solar cell are often labeled after the semiconducting material they are made. They can made of an individual layer or use numerous physical arrangement to take benefit of multiple absorption factors. The first-generation cell-also known as the wafer based cells are assembled by crystalline silicon, the commercially prime PV technology that contains poly and monocrystalline silicon. Out of these Monocrystalline PV module shows higher efficiency the Polycrystalline modules. [2]

Second generation solar cells are the thin film solar cells, which incorporate deformed silicon, CdTe and ClGS cells and are commercially substantial in utility-scale PV stations. These are slightly less expensive than the alternatives. [2]

The third-generation solar cells comprise a very small number of thin film technologies often described as emergent PV. Maximum of them have not yet been substantially applied and are still in improvement stage. [2]

1.6.3. Air Gap

The air gap between the module and the roof where the PV module is installed, that limits the heat transfer rate inside the air opening. The distance has a great impact as it provides enormous room to the wind velocity to pass through it.

Consequences have shown that at small wind velocity 0.5m/s, high temperature conduction influence the heat transfer process and superior efficiency can be accomplished by increasing gap size.

1.6.4.Shading Effect

The cells of solar PV module are connected in series, thus even a partial shade on the solar PV module reduces its performance to higher extend. Thus, it is essential to install the PV plant on shade free area.

1.7. Effect of module temperature on PV performance

The wavelengths of the radiations that reach the earth are between 250 and 2500 nm, and they are referred to as a terrestrial solar spectrum [4]. According to fig. 1.5, this spectrum is used for solar thermal and photovoltaic applications. As can be observed in fig. 1.5, a single junction crystalline solar cell can only convert a portion of this solar spectrum into electricity. As a result, the solar radiations in the solar PV that is not used are being absorbed in the solar cell material, which results in thermal losses.

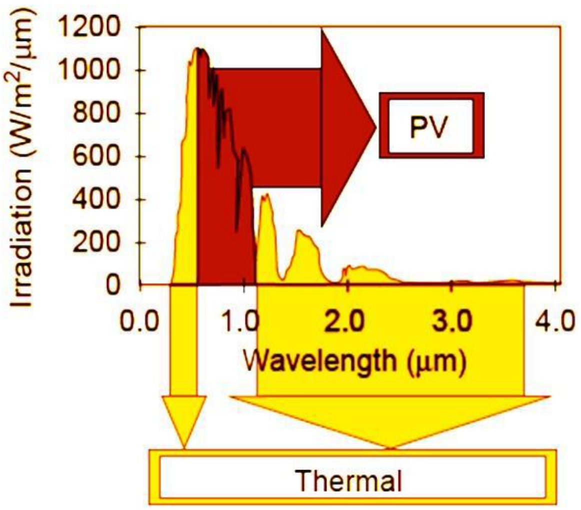


Fig. 1.5: Use of solar radiations in solar PV and Thermal systems [6]

As the solar PV modules in the solar PV plant are exposed to the entire solar spectrum, the unused portion of the solar spectrum heats the solar PV modules, reducing their electrical output, as reported in multiple studies and illustrated in fig. 1.7 [8-11].

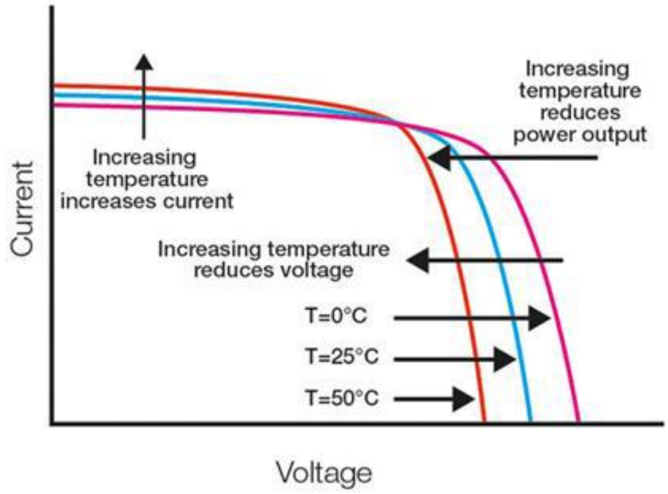


Fig. 1.6 Solar cell output at different temperatures [8]

Maintaining the lower operating temperature of the solar cells in PV modules is therefore necessary for the solar cells to perform better.

1.8. Concept of Agrophotovoltaic

Solar photovoltaic power plants have been gaining worldwide popularity, driven by advanced manufacturing technology and government policies. However, the efficiency of these solar photovoltaic plants is limited, requiring substantial land for installation. In the context of population growth and globalization, this has led to a scarcity of arable land. This situation has raised concerns about a potential future challenge: the Land Energy Conflict.

To address this issue, an innovative concept known as Agrophotovoltaics has been introduced. This concept allows for the simultaneous use of the same land for both solar power generation and farming, effectively integrating the two. Agrophotovoltaics (APV) also known as Agrivoltaics was introduced by German physicists Adolf Goetzberger and A. Zastrow in 1981[13].

In the Agrophotovoltaic system, the primary goal is to utilize the same plot of land for both agriculture and energy generation. Both these activities rely on the same energy source, sunlight. However, using sunlight exclusively for solar power generation would hinder farming on the same land. Therefore, Agrophotovoltaic systems aim to strike a balance between these two needs. This balance is achieved through the careful design of Agrophotovoltaic systems.

In Agrophotovoltaic systems, crops are typically grown in the spaces between rows of solar PV modules or beneath them. The optimal design incorporates various types of PV modules, including transparent and bifacial modules, specially engineered mounting structures, and thoughtfully designed plant layouts to enable partial shading in different seasons.

In essence, Agrophotovoltaic systems go beyond merely cultivating vegetation alongside a solar power plant. They involve the efficient integration of vegetation cultivation and solar PV installation to make the best use of available land, Different types of Agro- photovoltaics , criteria for selecting suitable farms/ crops, structures, and the use of different simulation tools etc. are elaborated in depth in Chapter 2 of this thesis.

1.9. Outline of the Present Work

In the present work, an experimental setup of a grid-connected rooftop solar PV system of 2.0 kW was designed, developed, and installed at Nagpur [21° 09' N, 79.07" E] India. The Solanum Lycopersicum (Tomato), Aloe Barbadensis Miller (Aloe Vera) and Spinacia Oleracea (Spinach) plants were cultivated below the 50% solar PV modules alternately to convert the half PV power plant into an Agrophotovoltaic system. The experiments were performed to compare the electrical and thermal performance of the conventional solar PV plant and the APV plant. Along with the power plant’s performance, the overall growth of Tomato, Aloe Vera and Spinach crops was also monitored throughout experiments. The experimental studies also include the investigations on effect of crop height on the thermal performance of the power plant and its effect on the power output of the plant.

To develop a framework to simulate the performance of the agrovoltaics system for given location, a theoretical estimation model has been developed. The model consists of systematic methodology to predict the performance of MW scale APV plant by considering the location of plant. The model is based on the estimation of solar energy at the location, estimation of PV module temperature by the method of Multilinear Regression analysis, estimation of PV output based on NOTC method.

The details of the study have been presented in this thesis. The thesis has been organized as follows.

Chapter-1

This chapter emphasizes the need for renewable energy. The limitations of conventional solar PV system and the potential land use conflict in near future. The chapter also highlight the concept of APV system and their benefits. The chapter concludes at the overview of the present research work.

Chapter-2

This chapter gives the in-depth literature review on the APV system and its various aspects. The chapter mainly highlights the concept of APV system, its various types, crop suitable for the APV systems, the pass work carried out on the APV system by the researchers. The chapter concludes at the research gap and objective of present research work.

Chapter-3

This chapter highlights the methodology adopted to acomplish the objectives. This chapter also discusses the experimental set up used in this study.

Chapter-4

This chapter reports the details of experimental studies and findings of the experimental works carried out using the developed APV systems. Majority the effect of different crops, different height of PV modules, on the electrical and thermal performance of the PV modules are reported.

Chapter-5

This chapter reports the performance analysis of APV systems based on the experimental studies carried out. The analysis majorly consists of effect of crop cultivation on the PV model temperature and their electrical output thereof. It also covers the crop yield in open sky farming and in APV system.

Chapter-6

This chapter aimed at development of an analytical framework to predict the performance of the APV plant at any given location. The theoretical frame work gives a predictive model for power estimation of the APV plant based on the reduction in PV module temperature in APV system. The predictive model considers the outcomes of the regression analysis of module temperature that was developed based on the experimental findings.

Chapter-7

This chapter presents the key findings from the current research work. The overview of the research is presented in the first section of the chapter, followed by a discussion of the key findings. The chapter concludes with an overview of the future research scope to develop the large scale APV systems.

CHAPTER-2

LITERATURE REVIEW

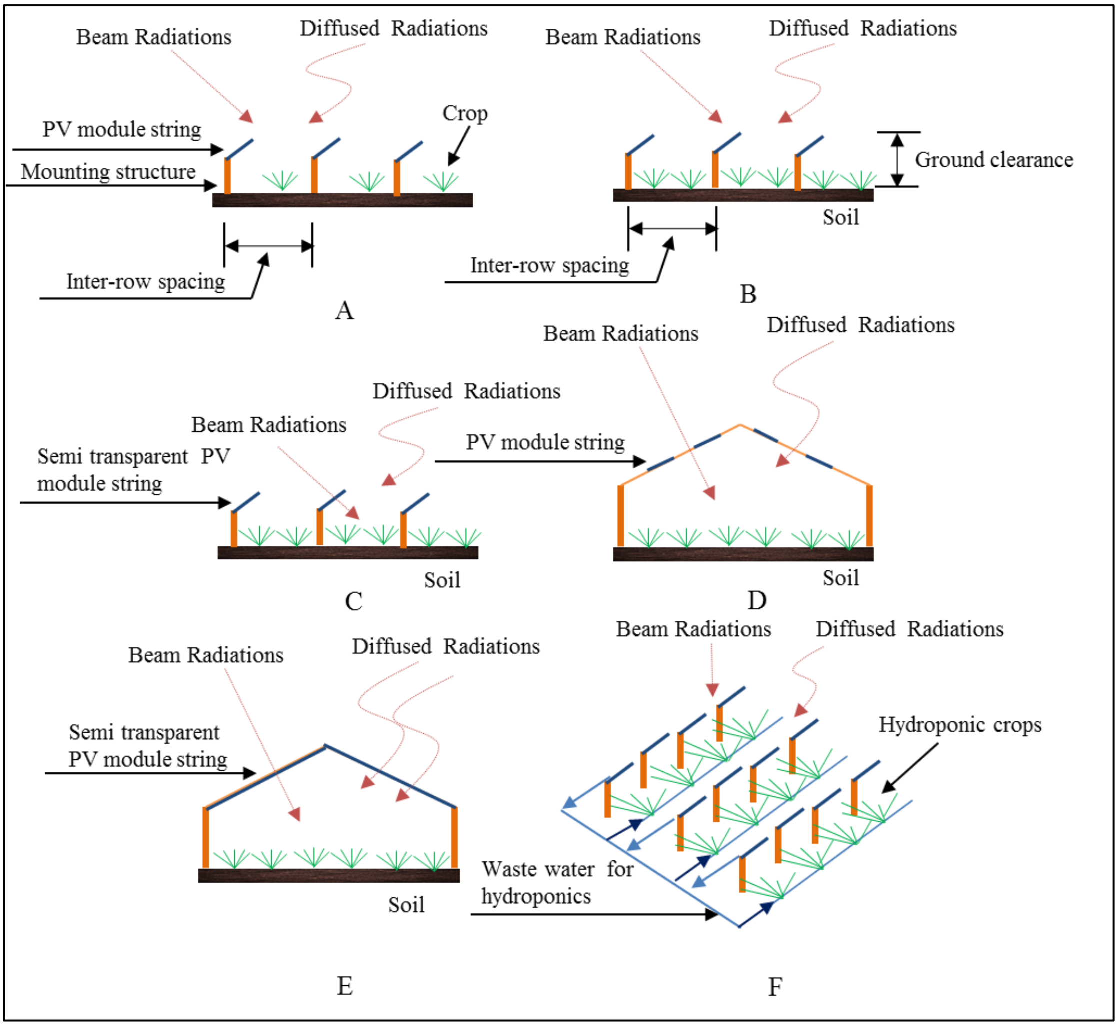
This chapter gives the in-depth literature review on the APV system and its various aspects. The chapter mainly highlights the concept of APV system, its various types, crop suitable for the APV systems, the pass work carried out on the APV system by the researchers. The chapter concludes at the research gap and objective of present research work.

2.1 The APV systems

Agrophotovoltaics (APV) also known as Agrivoltaics was introduced by German physicists Adolf Goetzberger and A. Zastrow in 1981(Goetzberger and Zastrow 2015).The typical solar photovoltaic plant has several solar photovoltaic modules connected in multiple strings. The appropriate inter-row spaces are provided in between these strings. Furthermore, for better ventilation and access, the solar photovoltaic modules are mounted at a certain height from the ground. Also, the modules are mounted at an optimum tilt angle to receive the maximum solar radiation throughout the year. In APV, the inter-row spacing, the space beneath the solar PV modules are utilized for crop cultivation. The best suitable crops for the APV systems are shade-tolerant plants.

2.2 Various types of Agrophotovoltaics systems

The APV systems are classified based on the location of crop cultivation and the type of PV modules used as shown in fig. 2.1



(A: APV with inter-row spacing (Patel et al. 2009), B: APV with inter-row spacing and ground clearance (Goetzberger and Zastrow 2015), C: APV with transparent modules, D: APV with- conventional solar greenhouse (Fatnassi et al. 2015), E: Greenhouse with transparent modules (Li et al. 2017), F: APV with hydroponic crops

Fig.2.1: Various types of Agrophotovoltaic systems [13]

As shown in fig. 2.1, several types of APV systems can be developed. The inter-row space and the ground clearance of the solar PV plant are utilized for the cultivation of shade-tolerant crops Fig. 2.1 (A),(B). The crops cultivated in the inter-row space receive both beam and diffused radiations however, the crops beneath the solar PV module can receive the diffused radiations and marginal beam radiations throughout the day. Another category of the APV system is the use of the semi-transparent solar PV modules Fig. 2.1 (C). In this case, the solar radiations corresponding to the response range of the solar PV module can be converted into electricity and the other direct and beam radiations can be absorbed by the crops and the soil. In another case, the crops can be cultivated in the greenhouse environment; where the top surface of the greenhouse can be partially covered by the conventional PV modules Fig. 2.1 (D). In this case, the solar radiation can penetrate inside the greenhouse from the uncovered greenhouse top.

In another arrangement, the semitransparent solar PV modules can be used to cover the top of the greenhouse Fig 2.1(E) to get more amount of sunlight inside the greenhouse. Thus, the same greenhouse can produce electricity and greenhouse crops simultaneously.

Fig. 2.1 (F) shows one of the futuristic arrangements - the use of hydroponics in APVs. In the hydroponic technique, the crops can be cultivated without soil by using aqueous solvents and nutrient solutions. In hydroponic APV, the idea is to cultivate the shade-tolerant hydroponic crops in the inter-row spaces and beneath the solar PV modules. As the hydroponic crops don't require soil, this kind of APV would be more suitable for rooftop solar PV plants. Furthermore, as shown in Fig. 2.1(F), the used water for cleaning solar PV modules can be used in hydroponic farming in APV.

2.3 The selection of suitable crops for the APV system

The selection of the most suitable crops is one of the crucial aspects of APV systems. The significant parameters for the selection of APV crops are as below.

- Requirement of direct sunlight
- Requirement of soil/land preparation
- Requirement of water/irrigation
- Climatic factors
- Root depth
- Height of the crop
- Transpiration cooling potential
- End utility/ market demand

The key aspects of all the above-mentioned parameters in connection with the APV system have been discussed in table-1.

Table-2.1: Factors to be considered for crop selection for APV systems

Sr.No.	Parameter	Relevance to APV system
1	Requirement of direct sunlight	The crops cultivated in the inter-row spaces and beneath the solar PV module would get the less amount of direct sunlight, the possibility of getting diffuse sunlight is higher. According to Gu et al.(Gu et al. 2002), plants use diffuse light more efficiently than direct light as it penetrates easily in the leaves and distributes evenly on its canopy. Thus, in APV, it is recommended to cultivate shade tolerant, Sciophilous, or shade-loving plants.
2	Requirement of soil/ land preparation	In APV, it is always recommended to select the crops that need less amount of soil and less land preparation. (Eg. Soil-less crops - like fruiting and leafy vegetables)
3	Requirement of water/irrigation	In the ground-mounted APV systems, excessive soil moisture may affect the PV foundation, thus it is recommended to select the crops that require less amount of water. (eg. Succulents)
4	Climatic factors	The growth of plants strongly depends on atmospheric temperature. Most of the crops have their optimum Accumulated Temperature (AT) limits (Hallett and Jones 1993). On the other hand, the solar PV module does not always convert all incident solar radiation into electricity; only a small portion of it does so, and the remainder is absorbed by the module, making the module hotter than its surroundings. Energy radiates from the heated PV module in all directions. If the structures are not built properly, heat is usually trapped beneath this heated PV module, causing the air beneath it to be warmer than the surrounding environment. Thus, a better choice would be to select the warm-season crops. (Beans, Eggplant, etc.)
5	Root depth	In the APV, the post-harvest land preparation should be as low as possible. Thus, shallow-rooted crops (root depth of 12-18 inches) are suitable for the APV systems.
6	Height of the crop	For low wind resistance and better structural stability of the PV installations, the optimum structure height is selected.

		Thus, it is required to select the crops suitable for the optimum ground clearance.
7	Transpiration cooling potential	One of the most significant physiological processes that plants go through is transpiration. When solar energy reaches a leaf, water evaporates from its surface through transpiration, absorbing the latent heat and transforming it into water vapour. As a result, the humidity of the air increases and the leaf's temperature decreases. The leaf takes in heat from the atmosphere around it to maintain equilibrium, which lowers the ambient temperature. (Gupta et. al. 2018). In APV, this type of transpiration cooling from the planted crops will aid to lower the temperature of the solar PV module, improving the electrical performance and life of the PV module. Most plants have some capacity for transpiration cooling. Moreover, in an APV system, crops with a higher transpiration cooling potential could well be chosen. Succulent plants may be a better option for APV systems as they store substantial water in their leaves and stems; thus, it causes more water to evaporate from the leaf surface. In order to maintain equilibrium, more heat from the environment must also be absorbed, which lowers the surrounding temperature and in turn improves solar PV module efficiency.
8	End utility/ market demand	The food crops, cash crops, horticultural crops, plantation crops, ornamental crops, medicinal crops can be cultivated in APVs.

2.4 The suitable crops for the APV system

Based on the criteria discussed in section 2.3, the different crops can be selected for APV systems. Furthermore, the crop selection principally depends on the geographic and climatic conditions of the solar PV plant location. The most feasible shade-tolerant crops suitable for APV systems in India are medicinal, vegetables, foods, and flower crops. The most suitable crops have been discussed in the subsequent text. Table-2.2 shows the medicinal crops, table-2.3 shows the other horticultural crops that include food crops, vegetables, and flowers.

Table 2.2: Shade tolerant medicinal crops for APV systems for Indian climatic conditions

Sr. No.	Name of the crop	Appearance	Suitable soil	Height of crop	Special features	Ref.
1	Malabar nut / Adulsa		well-drained wet soil	1.2-2.5 meters	Needs semi-shadow or shadow exposure	[13]
2	Tulsi		well-drained, moist soil	30-130 cms	Can be cultivated in soil-less systems too	[52]
3	Aloe Vera		all kinds of soil, Sandy soil	60-100 cms	• Tolerate some light shade. • Good transpiration cooling potential	[45]
4	Gotu kola/ Brahmi		Loose, sandy lome, clayey	60-90 cms	• Can tolerate heavy shade • Succulent leaves	[54,44]
5	Kalmegh		sandy loam to clay-loam soils	30-90 cms	withstand partial shade	[54]

6	Gandrayan		deep rich porous and moist soil	1-2 meter	Needs shady location	[54]
7	Pashanabhed		sandy, slightly acidic soils	30 cm	Grows better in shade	[54]
8	Periwinkle		Light soils	90 cms	Can grow in shade	[54]
9	SafedMusli		Sandy loam	25-30 cms	Partial shade tolerant	[54]
10	Long Pepper		well-drained, fertile black cotton soil	100-300 cms	25% shade is optimum	[54]
11	Mint		well-drained, rich soil	8-10 cms	Shade Tolerant	[56]

Table 2.3: Shade tolerant other horticultural crops for APV systems

Sr.No.	Name of the crop	Appearance	Suitable soil	Height of crop	Special features	Ref.
1	Spinach		well-drained, deep, loam soil rich in organic matter such as compost or composted manure	30 cms	Spinach requires cool weather Tolerate some light shade	[55]
2	Beets		Most, loose & Light soil	30-90 cms	Part Sun Tolerate some light shade	[12]
3	Lettuce		loose, cool soil with good drainage	15-30 cms	High light intensity with a shorter photoperiod	[16,17,24]
4	Peas		well drained, loose, friable and heavy soils	Bush peas: 60-90 cms Climbing peas: 180-240 cms	partial shade	[16]
5	Mustard Greens		moist, rich soil	90 cms	partial shade	[54]
6	Potatoes		Loamy and sandy loam soils, good drainage and aeration	100 cms	grow best in cooler climates	[53]

7	Radish		light, friable sandy-loam soils	30-45 cms	tolerant of some shade	[57]
8	Coriander		well drained loamy soil	60 cm	15-28°C Tolerate some light shade	[16]
9	Guar		well-drained, upland sandy loam and loam soils	60-100 cms	28-32 degree Tolerate some light shade	[16]
10	Fenugreek (Methi)		well drained loam or sandy loam soil	40-80 cms	15-28°C Tolerate some light shade	[16]
11	Garlic		sandy loam and silt loam soils rich in organic matter	30-90 cms	10-30°C Tolerate some light shade	[16]
12	Cucumber		Sandy loam to heavy soil	90-240 cms	25-35°C Tolerate some light shade	[24]
13	Tomatoes		sandy loam to clay, black soil and red soil having proper drainage	50- 150 cms	Partial shade 10-25°C	[30]
14	Maize		loam sand to clay loam.	208 cms	Partial shade	[19]

15	Wheat		Well-drained, fertile loamy and clayey loamy	60–88 cm	Temperature: Between 10-15°C (Sowing time) and 21-26°C (After sowing)	[15]

2.5 Work carried out on the APV system

Since the inception of APV systems, a lot of research work is being carried out on the feasibility investigation of APV systems at various locations and for different crops. As per the literature study conducted in the present study, the APV study can be broadly divided into two sections as - section i. The APV systems with crop cultivation in inter-row spacing and beneath the PV modules (ref. section 3.1) and section- ii. Greenhouse APV systems (ref. section 3.2).The significant research work carried out on APV systems has been discussed in the subsequent text.

2.5.1 The APV systems with crop cultivation in inter-row spacing and beneath the PV modules

In this category of the APV system, the crops are cultivated in the inter-row spaces between the two strings of the solar PV plant. Also, the land covered by the solar PV modules (beneath the solar PV module) is utilized for crop cultivation. The previous work mostly includes simulation of the performance of the APV plant (Patel et. al. 2009), simulation of the effect of full and partial shade of the PV panels on the crops(Goetzberger and Zastrow 2015; Marrou et al. 2013; Santra et al. 2017), economical analysis of the APV plants (Dinesh and Pearce 2016). The previous work also includes experimental analysis of the APV systems for different densities of the PV modules installed (Sekiyama and Nagashima 2019), fixed and sun-tracking PV modules (Amaducci, Yin, and Colauzzi 2020). Some of the research works focus on the study of the effect of microclimatic parameters on APV (Dupraz and Dufour 2011; Patel et. al. 2009), the growth rate of crops (Barron-Gafford et al. 2016; Dupraz and Dufour 2011), land equivalence ratio (Amaducci, Yin, and Colauzzi 2020), water productivity (Elamri et al. 2018),Evapotranspiration and soil- water balance (Amaducci, Yin, and Colauzzi 2020), selection of crops for the APV systems(Santra et al. 2017), etc. The significant work has been discussed in the subsequent text.

Patel et al. [14] studied the effect of various environmental factors (light intensity, relative humidity, air temperature) on the APV system installed in India. A polycrystalline solar PV plant of 7.2 kW capacity having a total of 48 PV modules of 150 W each has been installed. The PV modules are inclined at latitude angle, the elevation of the structure is 3 m and the inter-row spacing is 1.36m. The plant covers around 153 sq. m area(fig.2). The study concludes that the temperature of the open field is always higher and the relative humidity of the open field is always lower as compared to the space below the solar PVmodules. On average, 55% reduction in the sunlight below the solar PV modules has been reported.

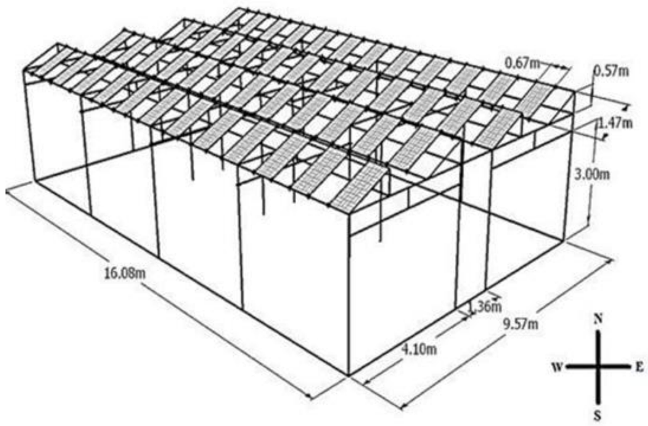


Fig.2.2: The elevated APV system [14]

Dupraz et al. [20] carried out simulation studies on the performance of the APV system installed in France. Monocrystalline solar PV modules with a mounting height of 4 meters and inter-row spacing of 1.64 meters have been installed on 820 sq. m land. The simulation studies were carried out using the Radiation Interception model and

STICS Crop models for the two different densities of the PV modules. The study concludes the overall land productivity of 73% in APV systems.

Gafford et al. [21] have performed experimental and simulation studies on the APV systems in the USA. The study was aimed to investigate the microclimatic conditions, PV module temperature, the growth rate of the plant, moisture, and temperature of the soil in the APV system. The PV modules are mounted 3.3 meters above the ground at a tilt angle of 32o. The light level, relative humidity, and the air temperature below the PV module have been recorded at 2.5 meters above the ground and the soil temperature and the moisture have been recorded 5 cms below the ground level. The system performance for three different crops viz. Chiltepin pepper, jalapeno, and cherry tomato has been studied. The study concludes that the Chiltepin pepper production has increased three times as compared to open farming. Apart from the food production, the study also concludes that the APV systems are beneficial for saving irrigation water and improves the electricity production from the PV modules.

Harshavardhan et al. [17] have studied the simulation model on the APV system installed in the USA. The study includes the performance estimation of the APV system using PVSyst and STICS crop model. The two configurations, i.e. ground-mounted and the stilt mounted solar PV panels are considered. The ground-mounted solar PV modules are installed at a height of 1m with 6m inter-row spacing and in another case, the height of the stilt is 4 m from the ground. The lettuce was cultivated in both the configurations in the inter-row space and below the PV modules. The study concludes the 30% increase in the economic value by the APV system.

Goetzberger et al. [13] have derived the mathematical formulation on the fraction of light reaching the ground in different APV configurations. The mathematical formulation shows the dependence of the fraction reaching the earth's surface is on the PV module dimensions, inter-row spacing, hour angle, elevation angle, and zenith angle. The mathematical model concludes that the fraction of light reaching the ground under the PV module (installed at 2 meters height) for 480elevations is 0-64%, and for

580 elevations, it was about 11 – 75%. The study shows that around two-thirds part of the total incident light is available for crop cultivation in the APV system.

Marrouet al. [15] have conducted experimental work on the APV system installed in France. The performance of the three different configurations – inter-row spacing of 1.6 m, 3.2 m, and open sky are investigated for lettuce, cucumber, and durum wheat. The changes in crop growth rates, air, soil, and crop temperature, relative humidity have been studied. The study concludes that the mean air temperature and relative humidity below the PV modules remain unaffected in the APV system as compared with the open sky conditions. However, the soil temperature reduces significantly. In APV, the crop temperature decreases in day time, but increases in the nighttime. The study concludes that, in the APV system, the growth rate of crops may reduce their initial growth period, thus the study recommends studying the developmental stages of crops before selecting them for APV systems.

Malu et al. [23] have proposed the APV system for grape farming in India. The grape plants are supported by a trellis, and the space between two trellises is usually unutilized. It is proposed to install the solar PV modules on these unutilized spaces between grape trellis as shown in fig.3. The simulation study has been carried out to estimate the technical and economical performance of the APV system for grape farming. The performance of the APV system has been estimated using the SAM model of NREL. The study concludes that the APV system can increase the overall economic value of grape farms by 15 times as compared with conventional farming.

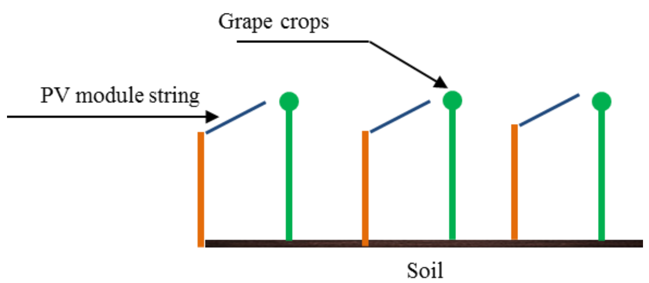


Fig.2.3: APV with Grape Crops [23]

Amaducci et al. [19] have carried out simulation studies on APV systems in the maize farm using sun-tracking solar PV modules in Italy. In this simulation work, For crop yield simulation and optimization of the design of PV infrastructure, a software model - GECROS – Generic crop growth simulator has been developed. According to this study, around 13 to 29.5% reduction in the sunlight for the crop in the APV system has been estimated. However, the study concludes that, instead of the static solar PV modules, the sun-tracking solar PV modules can perform better in APV systems.

Priyabrata et al. [16] conducted analytical studies on the estimation of shading by the installed solar PV modules in APV systems. The length of the shade cast by the solar PV modules on the ground is estimated by using solar geometry and time of the year at a given location. The study also provides the feasibility of various medicinal, vegetable, and spice crops for APV systems.

H. Marrou et al. [24] have conducted experimental work to analyze the effect of shading on crop growth in APV systems. In this study, East-west oriented solar PV modules are mounted at 250 inclined and are 4 m above ground. The three strategies – full density, half density, and full sun cropping have been explored. The study concludes that around 14-29% saving in the evapotranspiration water of crops is possible in the APV system. The study proposes four significant drivers of crop selection in APV systems - climatic demand at canopy level, a fraction of radiation intercepted by the vegetation, plant stomatal conductance, and soil surface hydraulic conductance. Further, it has been recommended to select the crops having a rapid rate of soil covering.

Adeh et al. [25] have carried out experimental work to investigate the effect of various atmospheric and geographic conditions on the APV crops. The study focuses on the effect of PV module shade on the surrounding humidity, microclimatology, use of water, and production of biomass. It was observed that the soil under the PV module was always maintained with higher moisture content. The study concludes that in wet winters, for semi-arid pastures of the land the productivity can be increased to 90% in APV systems. The study also recommends maintaining uniform shadow patterns by placing the solar PV modules at appropriate locations.

Elamriet al. [22] have carried out experimental work on the investigation of the effect of static and sun-tracking solar panels on the performance of the APV systems with lettuce crops in France. The study focuses on the study of water productivity and land equivalence ratio with static and dynamic solar PV panels installed in the APV system. The study recommends exploring the performance of the APV system with sun-tracking solar panels for different climatic conditions and various crops.

The experimental work has been carried out to investigate the performance of the stilt mounted APV system with corn as a crop in 100 sq. meter farm land in Japan by Takashi et al. [18]. The three APV configurations – no module, high density, and low-density PV modules have been studied as shown in fig. 4. The study concludes that the corn yield per square meter is larger by 5.6% as compared to the no module configuration

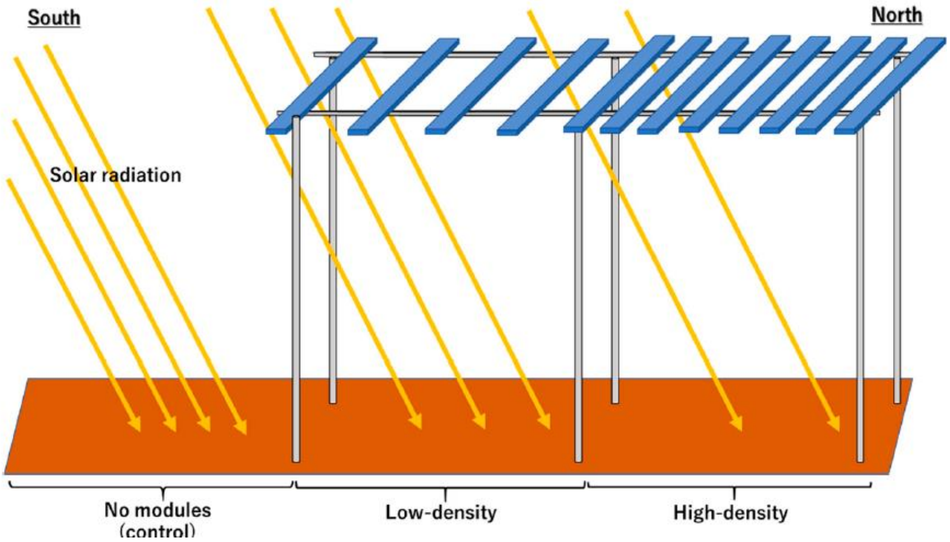


Fig.2.4: Low-density and high-density APV system [18]

2.5.2 Greenhouse APV systems

In this category of the APV system, the crops are cultivated inside the greenhouse (polyhouse). The top cover of the greenhouse is partially covered with solar PV panels. Thus, the sunlight can pass inside the greenhouse from the uncovered top surface and its sidewalls. The previous work mostly includes greenhouses with double film, brick, semi-transparent PV modules mounted on the top of greenhouse, economic and social aspects [26], simulation studies on microclimate [27], greenhouses powered by solar PV [28], and dynamic PV modules [29]. The significant work has been discussed in the subsequent text.

Changsheng et al. [26] have studied the economic and social performance of the greenhouse APV system in China. In this study, five different combinations of the APV system have been studied viz; double film column, partly shaded spring and winter, bricked winter, and terrace arrangement (with semi-transparent PV module) as shown in fig. 2.5. Tea, edible mushroom, season vegetables have been cultivated in the greenhouse APV systems. The economic indicators such as Net Present Value, Rate of Return, Economic ratio of input-output, payback period have been studied. According to the study, the part shaded greenhouse APV systems have the highest annual return on investment and it is around 20%. The payback period of the greenhouse APV system varies from 4-8 years depends on the crop.

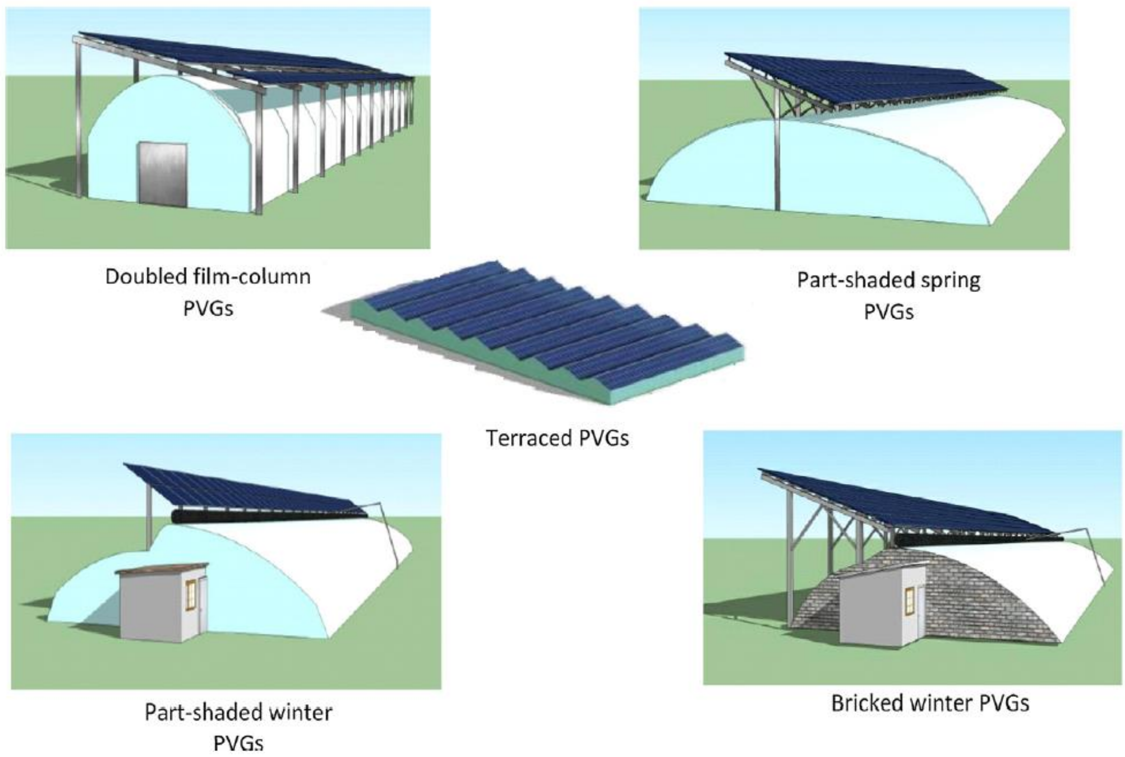


Fig. 2.5: Different combinations of the APV system [26]

Fatnassi et al. [27] have carried out simulation studies on the microclimate inside the solar APV greenhouse. In this study, the APV greenhouse consists of asymmetric and venlo arrangements with a straight line and checkboard solar PV modules installed on the top. In both the arrangements, the tomato crop was considered for the simulation. The numerical study has been conducted using the CFD package to investigate the microclimatic conditions, light transmission, and airflow inside the greenhouse. The study concludes that the Venlo type of greenhouse with checkboard arrangement of the solar PV modules gives 46% light transmission inside the greenhouse.

Marucci et al. [29] carried out experimental and simulation studies on the greenhouse APV systems with the manually adjusted dynamic PV modules and the reflective glass mirrors. In this study, the PV module strings are installed on the roof of the greenhouse keeping the gap between the strings to allow sunlight penetration inside the house. To improve the system performance, the highly reflecting aluminum mirrors are used to reflect the additional sunlight onto the PV modules as shown in fig. 6. The study analyzed the effect of the dynamic tilt of the PV module on the microclimatic condition inside the greenhouse and on the power production. It has been reported that the dynamic tilt of the PV module is very beneficial in the APV system as it gives the provision to manage the sunlight entry inside the greenhouse. Though the power generation by the PV module is completely utilized by the greenhouse (to maintain the airflow and temperature), a similar concept can be applied to the large-scale commercial greenhouse APV system to improve the overall performance.

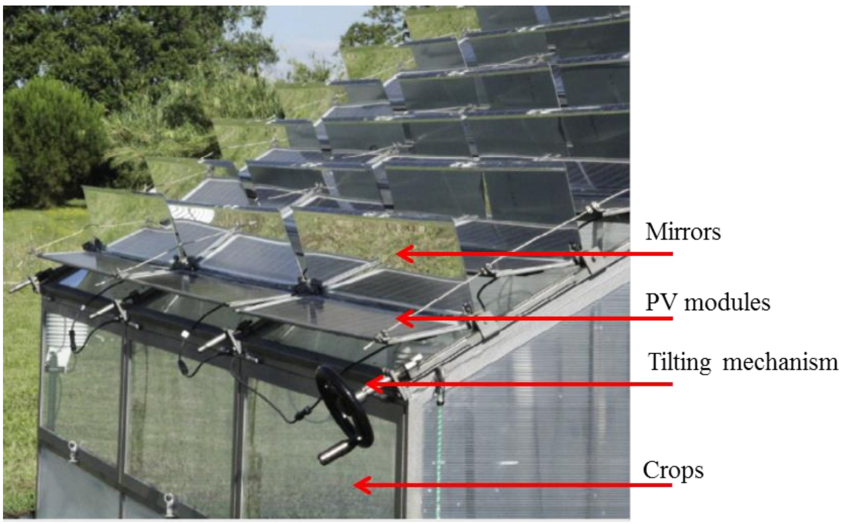


Fig. 2.6: APV with highly reflective Aluminum mirrors [29]

Kadowaki et al. [28] have studied the performance of the greenhouse APV system with hydroponically grown Welsh Onions in Japan. In this study, the effect of the straight-line and checkerboard arrangement of the solar PV modules on the shade and consequent crop growth has been analyzed. A total of 13% of the greenhouse roof area has been covered by solar PV modules. The study concludes that the straight-line PV arrangement gives better electrical output but reduces crop growth whereas the checkerboard arrangement gives better crop growth but less electrical output. Thus, the suitable arrangement or the combination can be chosen depends on the requirement.

Cossu et al. [30] adapted new structures for designing PV greenhouses with economic convenience investment and plant physiology. The climate inside a greenhouse with photovoltaic (PV) modules covers 50% of the roof area. The experiments have been conducted in Decimomannu (Sardinia, Italy) for horticulture to investigate the microclimate conditions within these already-existing structures and generate empirical findings on their agronomic viability. The crop selected for testing purposes was tomato. This study measured the reduction in solar radiation, which was on average 64% on an annual basis, varying from 82% for regions under PV covers to 46 percent for areas under transparent covers. When compared to standard greenhouses, this situation reduced tomato yields, but PV energy generated a significant profit.

Ezzaeri et al. [31] performed an experimental investigation on the Atlantic coast of Morocco. The tests were conducted in an experimental Canary greenhouse with flexible photovoltaic panels covering 10% of the total roof area as shown in figure 7. The shade of photovoltaic panels impacts the production of fruits. The panels arranged a checkerboard pattern it increases the occupancy rate by 10% on the tomato yield. This study concludes that the photovoltaic panels on the roof gives a beneficial effect on the crops as well as the fruits.

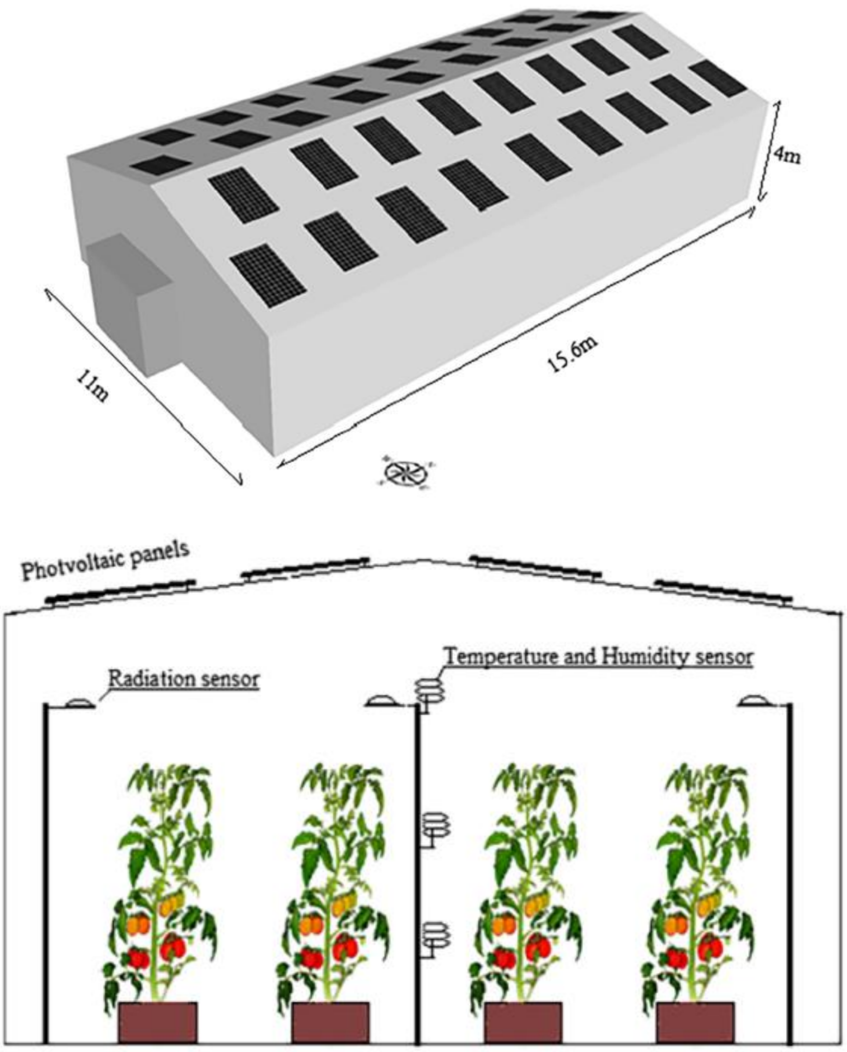


Fig. 2.7: a. Position of photovoltaic panels & b. Experimental setup [31]

2.6 Agrophotovoltaics – another way for thermal management of PV modules

The terrestrial solar spectrum is not monochromatic, it is in the range of 200 - 2500 nm; it consists of UV, visible and infrared radiations. The commonly used C-Si single-junction solar cells have a limited spectral response range (750 to 1125 nm) and thus the entire terrestrial solar spectrum cannot be used effectively for photoelectricity(Joshi and Dhoble 2018a). When the solar cell is exposed to sunlight, the photons other than its response range are getting absorbed in the solar cell material. This leads to elevate the operating temperature of the solar cells. The output of the solar cell reduces with increasing cell temperature. Thus, it is always desirable to keep the solar PV modules at lower operating temperatures. According to the standard test conditions (STC), the standard operating temperature of the solar cell should be 25 oC. However, due to the absorption of solar radiation, the PV module temperature is usually greater than STC, even during the winter seasons in the tropical region. Thus, for better performance, it is required to either extract the heat from the PV modules or maintain the surrounding temperature as low as possible.

Several techniques have been invented to extract the heat from the solar PV modules. In most of these techniques, fluids like water, air, thermic oils, etc. are circulated in contact with the solar PV modules to keep them at lower operating temperatures(Joshi and Dhoble 2018b). In the present study, it has been hypothesized that, in agrophotovoltaics, the cultivated plants below the solar PV modules can reduce the surrounding temperature by the process of transpiration cooling. Thus, it will help to reduce the module operating temperature and improves its performance.

Transpiration is one of the most important physiological processes that plants undergo, as it influences the temperature of their surroundings when exposed to sunlight. Water emerges from the leaf's surface through transpiration when solar energy hits it, absorbing the latent heat and converting it to water vapour. As a result, the atmosphere's humidity rises and the temperature of the leaf falls. To maintain equilibrium, the leaf absorbs heat from the surrounding atmosphere, lowering the ambient temperature. (Gupta et al. 2018). Greg A. Barron et. Al. (Barron-gafford et al. 2016)have carried out the experimental studies on a 3.3m PV array with Chiltepin pepper, Jalapeno, and cherry tomato crops in the agrophotovoltaics installation. According to their study, the solar PV modules in the agrophotovoltaics system were cooler by around 8oC as compared with the conventional ground-mounted system.

2.7 Research Gap

1. Several techniques have been reported to maintain the lower operating temperature of the solar PV modules. However, these techniques are yet to reach the level of commercialization due to retrofitting cost, auxiliary power consumption and maintenance difficulties.
2. The most of the experimental studies on agrophotovoltaics have been reported

considering climatic conditions of Montpellier, France/ Kansans, US regions. No significant studies have been reported for its implementation in India so far. Furthermore, In the previous studies the performance of the agrophotovoltaics system using lettuce, grapes, aloe vera, maize plants have been investigated. Thus, in the present work it is proposed to investigate the feasibility of more such crops for agrophotovoltaics suitable for Indian climatic conditions.

3. Many investigators are working in the area of agrophotovoltaics since 1980, however, the major focus is being given to increase the land use efficiency only. No significant work has been reported on the electrical performance improvement of the solar PV modules. Thus, in the present work, it has been proposed to investigate the performance improvement of the solar PV module in Agrophotovoltaics.

2.8 Objectives

The main objectives of the present research are,

1. To investigate the effect of integration of agrophotovoltaics with the solar photovoltaic systems on module operating temperature.
2. To investigate the effect of weather and operating conditions on the performance of APV.
3. To develop correlation for predicting the performance of APV under different locations and weather conditions.

Chapter-3

Methodology and Experimental Setup

A methodical approach has been developed to accomplished the objectives of the current study. The depoted methodology is described in detail in the current chapter. Also, this chapter provides a detailed information on the experimental setup. It's design consideration and installation in detail.

3.1 Methodology

As stated in chapter 2, the analysis of the effect of various parameters on the performance of APV system and the development of methodical framework for the prediction of APV performance are among the main objectives of this study. Accordingly the methodology has been developed which includes experimental study and the theorotical models. The detailed methodology has been shown in fig. 3.1

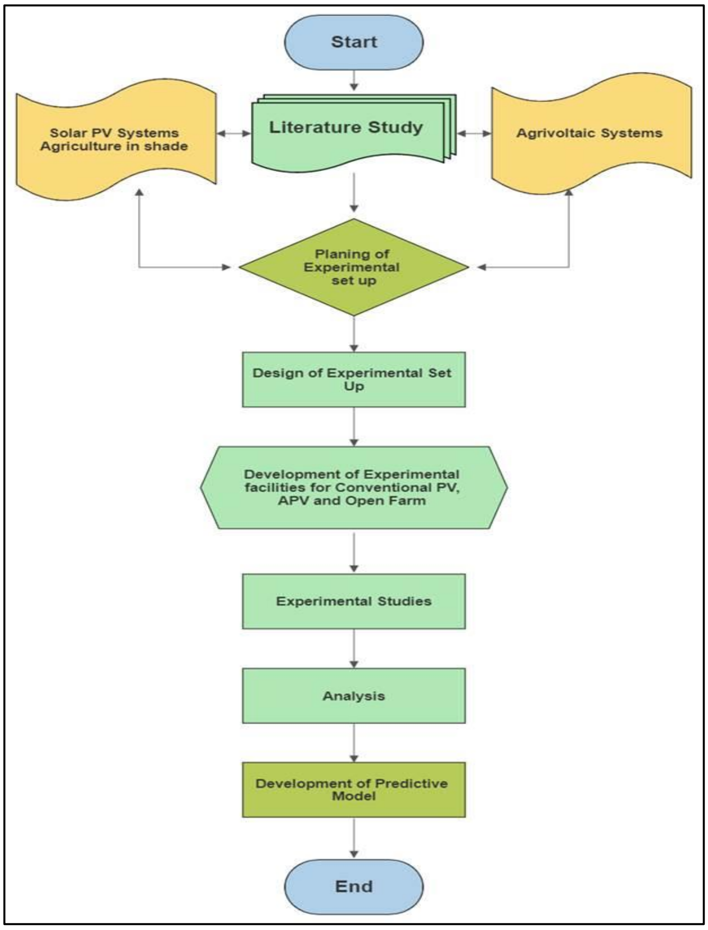


Fig. 3.1 Methodology of Experiment

As shown in figure 3.1 the methodology has been divided in three major phases.

Phase-I: Literature study, design and development of experimental setup. (Chapter 3)

Phase-II: Experimental Investigations (Chapter 4)

Phase-III Development of theorotical framework to predict the performance of APV system. (Chapter 6)

The following paragraphs describe all the phases in detail with reference to Fig.3.1.

3.1.1 Literature study

An extensive analysis of literature was carried out to gain the in depth knowledge of solar PV systems. Factors affecting the performance of PV sysyems, need of cooling of PV modules, concept of APV system, it's classification, various parameters affecting the performance of APV system, characteristics of various crops those can be cultivated with APV system, etc. Chapter 2 of this thesis covers all the details about this literature review.

After a detailed literature review the methodology for the present research work has been formulated. As discussed in section 3, the phase-I of the study includes the design and development of experimental setup, for this a detailed planning was made, as described in the subsequent text.

3.1.2 Planning of experimental setup

The following parameters are taken into account while planning the experimental setup.

- The capacity of the APV plant
- The location of plant installation
- Suitable crops for the experimentation
- Parameters to study during experimentation
- Cost of the system, available space, labours, grid connectivity, operational comfort and safety.

In addition to these, several other factors were taken into consideration right from selection of appropriate system components, mounting of rooftop of a building and so forth to make the suitable experimental setup to accomplish the planned experimental study.

3.1.3 Design of experimental setup

The design of experimental setup majorly takes into account the design of open sky farm and the APV farm. The first and important aspect in the design is correct choice of the crops to be cultivated.

3.1.3.1 Selection of crops for APV system

The selection of most suitable crop for the experimental studies is one of the major aspects in this study. Figure 3.2 shows the important criteria those were taken into account while selecting the appropriate crop for the present studies.

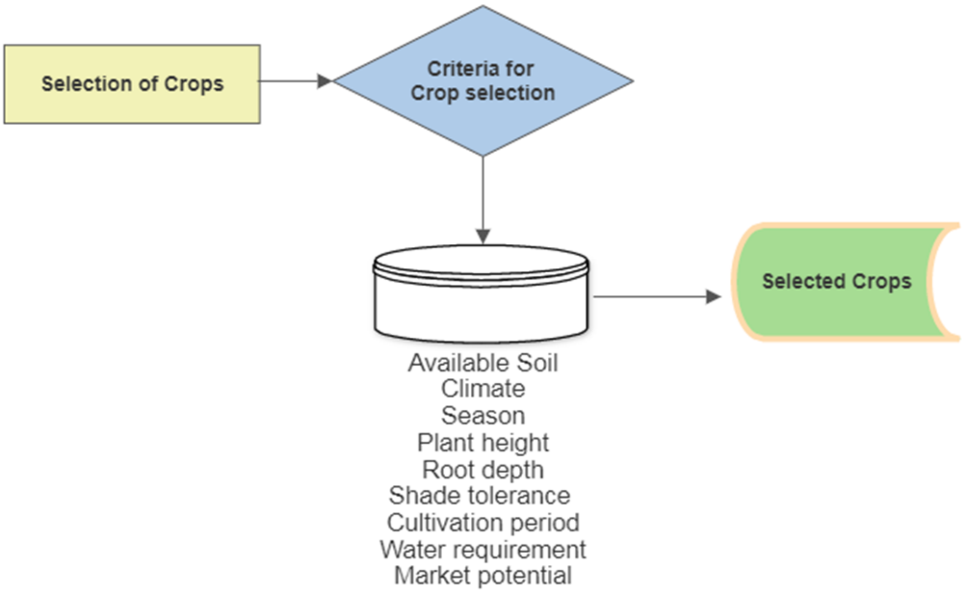


Fig. 3.2: Selection of crops for APV system

The following parameters were considered while selecting the crops in the present study.

- **Available soil**

  The quality of soil is a major decision factor for the APV plant. The available soil, its fertility and capabilities to grow the shade tolerant plants for the APV systems are few significant aspects. All the available soil on land is not fertile, the mineral component, organic matter, water holding capacity, it's pH value are some of the important parameters need to consider. In the present study, the location of installation of the experimental setup was selected as Nagpur [21° 08' N, 46.72" E]. The available soil in the region mostly includes Sandy loam, allovial, black cotton, well drained red loam soils. (Considering the aforementioned factors) Selecting the crops for the present study that are best suited to the available soil of the region was one of the crucial stages in this study.

- **Climate and seasons**

  Climate is considered as one of the most influential factors in agriculture. The climate affects the soil properties, temperature of atmosphere, seasons, length of crop growing period, sunlight, requirement of watering, humidity, crop growth and health. At the location of the present experimental study the climate is a tropical and semi arid climate. On an average the climate in the region is oppressive and it is not year round. Broadly the climate shows all the three seasons viz; Summer, Winter and Mansoon in the region of the present experimental study.

- **Plant Height**

  The another important aspect while selecting the crop for the APV system is the height of crop. When it comes to cultivation of crops beneath the solar PV modules or even in the inter row spacing of the solar PV plant, the height of the crops must be considered. In the present study the crops were cultivated beneth solar PV modules which were installed on a building rooftop with suitable inclined structure giving maximum height of 1.5 meters from the ground. Thus it was imperative to select the crops which can grow to a maximum height as that of PV plant installation.

- **Root Depth**

When it comes to an open sky conventional farming on the agricultural land, the depth of the roots may not be a significant parameters. But, in case of the APV system which is to be build on the rooftop of the building it becomes most crucial to select the crops having limited root depth so as to accommodate those in a suitable cultivation platform and integrated with the solar PV system to develop a APV plant.

- **Shade tolerance**

  As in APV plant, the crops are generally cultivated beneth the solar PV modules or in the inter row spacces in the solar PV plant, the crops get limited amount of sunlight throught the day. Thus it is essential to select the shade tolerant crops for the APV system. In the present study, the solar PV modules are mounted on a fixed non-tracking structure and the crops are cultivated beneth the solar PV module thus the shade tolerance of the crops is considered cautiously while selecting the crops.

- **Cultivation period and growing period**

  In the present study, the effect of crops on the microclimate below the solar PV module, different height of the crops, overall productivity of the APV system and the performance of the plant in different seasons were planned to study.

  According to the planned methodology different crops suitable to different seasons were to be selected for the study. Thus, taking all these in account the crops were selected having the average period of cultivation and growing was around 3 months for the single crop.

- **Market Potential**

  One of the aspects of the present study is to develop the APV system suitable for the region of the study. Thus the marvel potential of the crops was also taken into account while selecting the crops in the present study.

  Considering all the above factors, the three crops were selected for the present study as shown in table 3.1

Table-3.1: Selected crops for APV systems

S n.	**Name of Crop**	**Sunlight requirement**	**Soil requirement**	**Plant height**	**Growing period**	**Ref.**
1	Spinacia Oleracea (Spinach)	Low moderate	well-drained, loam	8-12 Inches	90 Days	[55]
2	Solanum Lycopersicum (Tomato)	Low moderate	Sandy loam to clay, black soil	10-18 Inches	70 Days	[30]
3.	Aloe barbadensis miller (Aloe Vera)	Tolerate some light shade	All kinds of soil, Sandy Soil	60-100 cm	90 Days	[45]

3.1.4 Planning of APV farm

After selecting the suitable crops for the purpose of experimentation the planning for APV farm was executed. Figure 3.3 shows the planning of APV farms. While planning the APV farm the following significant factors were considered.

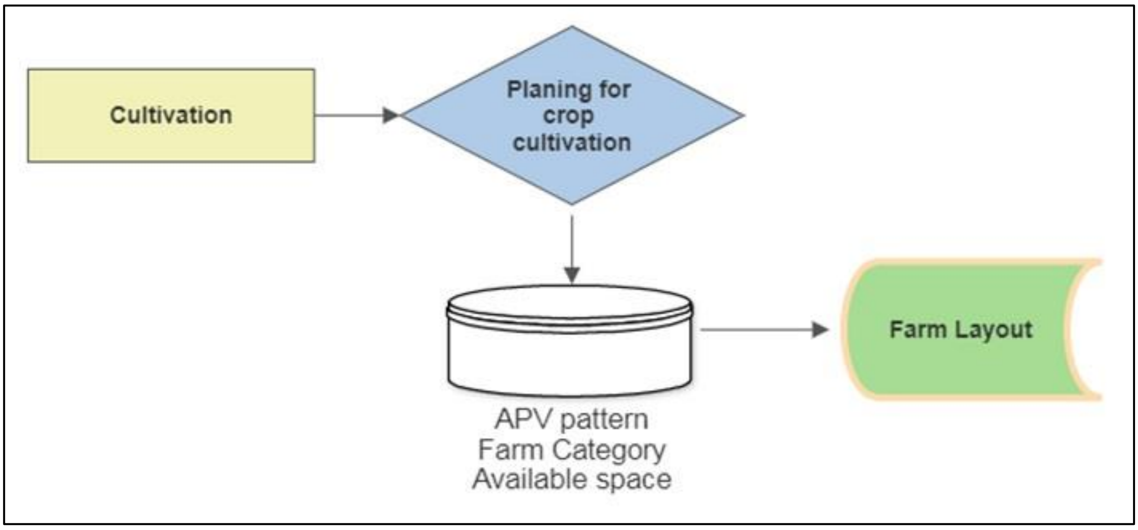


Fig. 3.3: Planning of APV farm

- **APV pattern**

As per the literature study different pattern of APV system includes checkerboard, in-line pattern, etc. Out of all these patterns the in-line cultivation of crops selected in the present study.

- **Farm catagory**

As discussed in chapter 2, there are several types of APV systems developed so far. These mainly include APV with crops below the PV modules, APV with inter-row spacing, APV with inter-row spacing and ground clearance, APV with transparent modules, APV with- conventional solar greenhouse, Greenhouse with transparent modules, APV with hydroponic crops. Out of these, cultivation of crops below the PV modules was adopted in the present work.

- **Available Space**

As stated in the preceding text, the experimental setup was designed for the rooftop of a building. The total capacity of the solar PV plant was 2kWp using the polycrystalline PV modules (details are discussed in section 3.1.4). Thus for a 2 kWp system around 18 m^2 space was available for the cultivation of the crops.

Taking all the above points into account the three selected crops were grown in the organised manner beneth the solar PV module. The crops are cultivated in the trays. Figure 3.4 shows the layout of the APV farm.

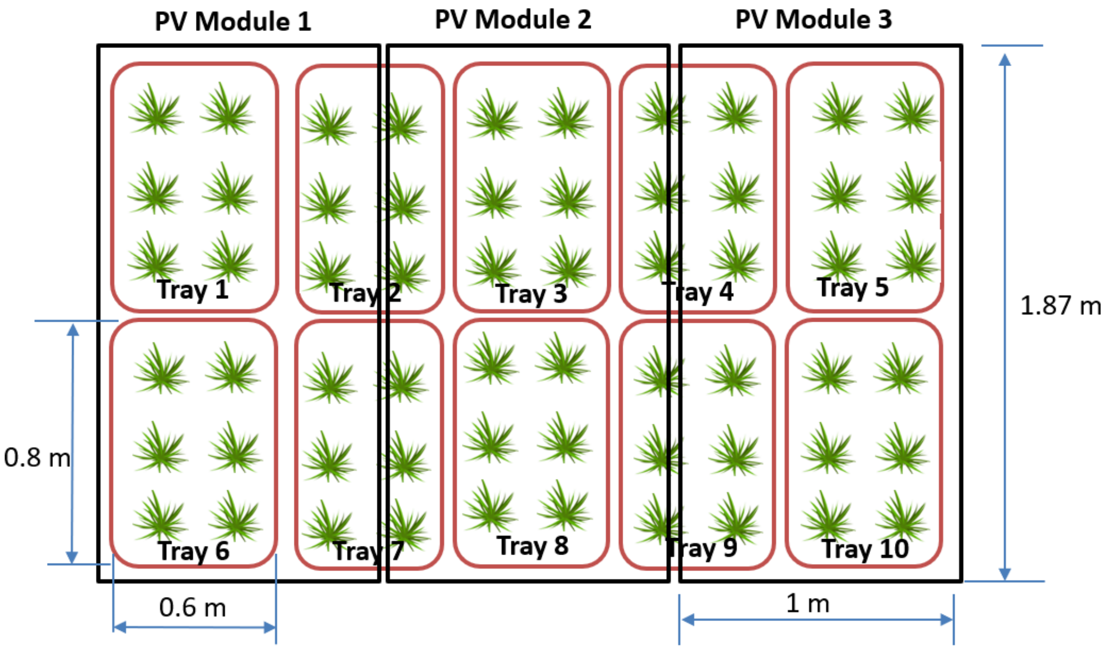


Fig. 3.4: Layout of APV farm

As shown in figure 3.4, the 10 number of trays af dimensions 0.8 m x 0.6 m were selected for the available footprint area of 0.48 m^2. Thus in total approximately 3 to 4 number of trays get accomodated below one solar PV module, and in all 10 number of trays were arranged below 1 kWp, 3 PV modules in the system. Figure 3.5 shows the steps followed in the development of APV farm and Figure 3.6 shows the different stages of cultivation.

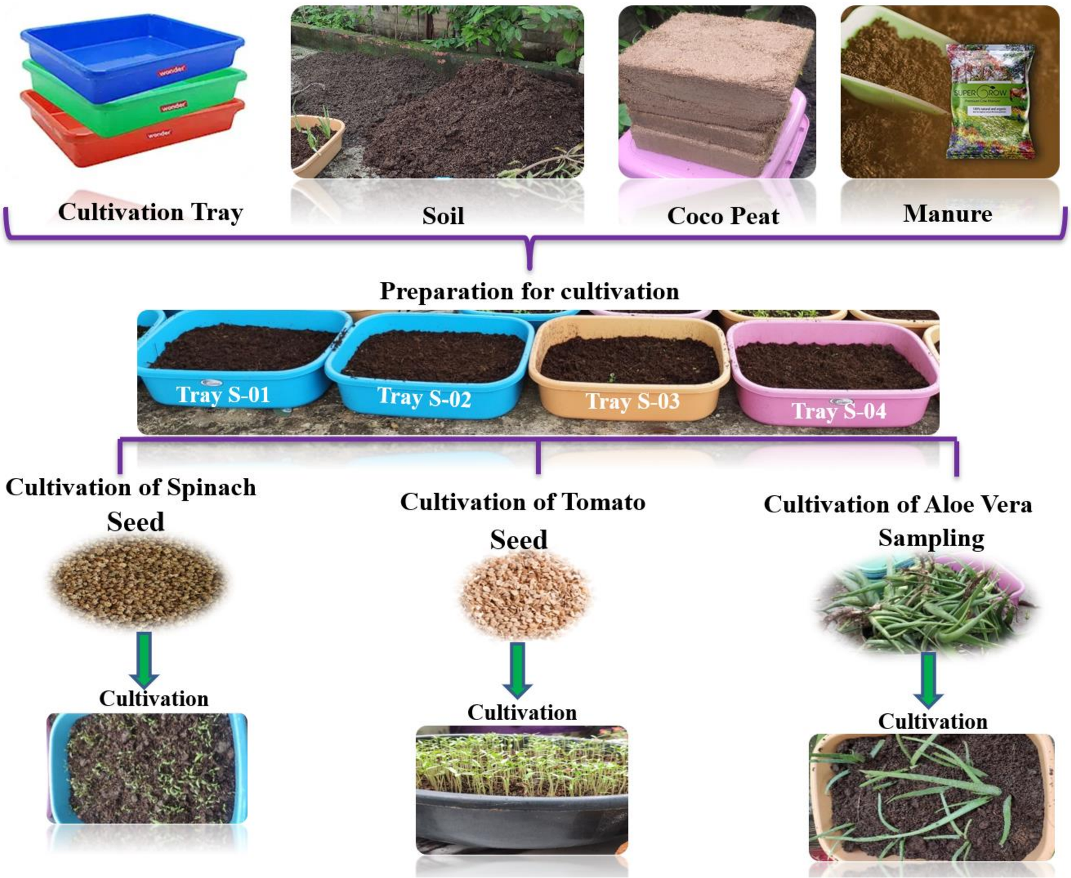


Figure 3.5. Steps followed in the development of APV farm

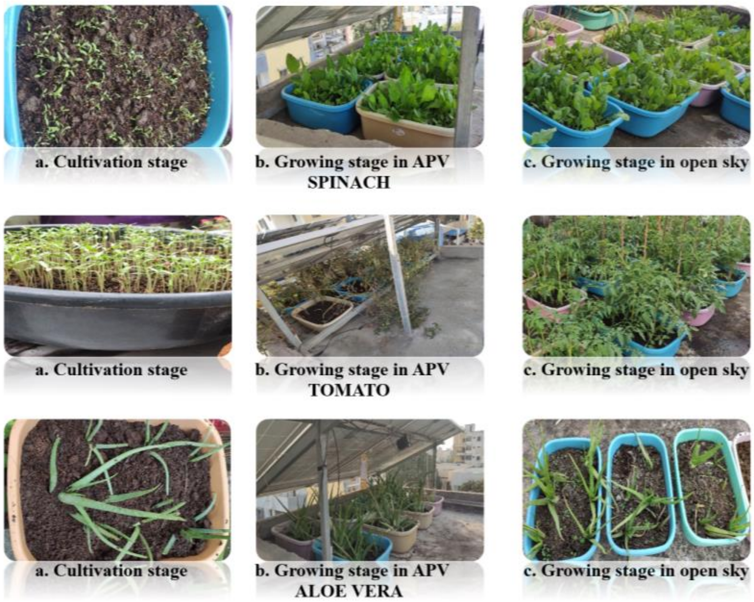


Figure 3.6. Different stages of cultivation

3.1.5 Experimental Set-up

The experimental setup has been divided in three groups viz

a) Conventional grid connected rooftop PV power plant (1kWp)
b) Agrophotovoltaic solar PV power plant (1kWp)
c) Open sky farm (Reference case for comparision of Agricultural field)

The conventional grid connected rooftop PV power plant and the Agrophotovoltaic solar PV power plant are of exactly same specifications, only the later has crops cultivated below the PV module. The significant design of the experimental setup are shown in figure 3.7

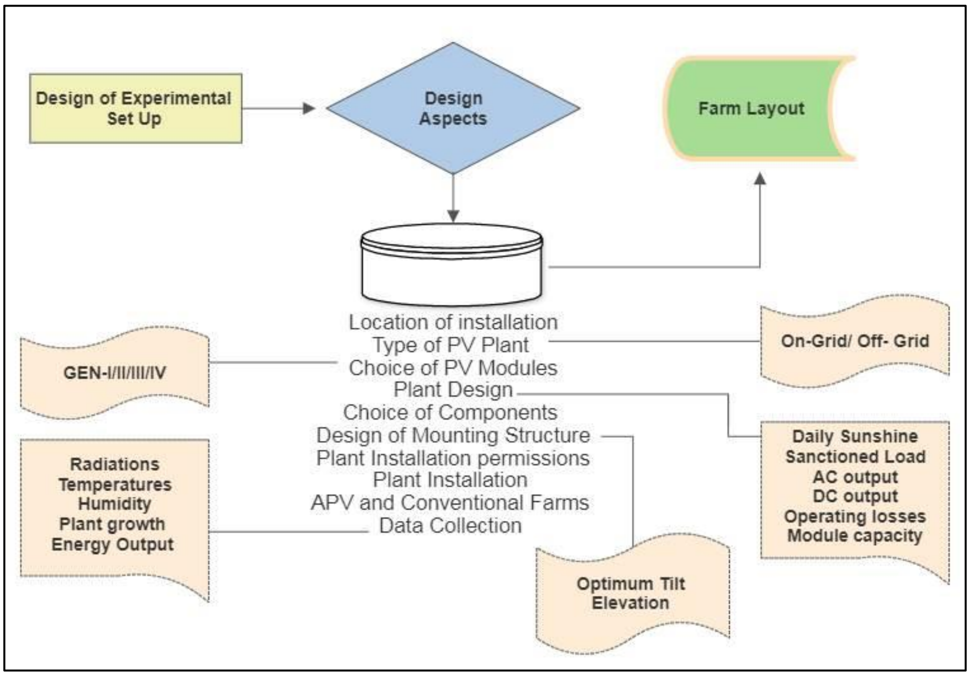


Fig. 3.7: Design of Experimental set up

The following paragraphs explain the considered design aspects in detail.

- **Location of the installation**

As stated in the preceding text the location of the experimental setup was nagpur a place in the tropical region having abundant amount of solar radiations throughout the year. On an average the day length in the region is around 10 hours and as shown in figure 3.8, the Global radiations are in the range of 600-1000 W/m^2, the radiation energy of around 4-7 kWh/m^2 day is available. The climate is generally hot with ambient temperature in the range of 25-45^{o}C. All the conditions make the Nagpur location suitable for the present experimental study where it is intended to study the effect of crop cultivation on the microclimate around PV modules and potential of PV module cooling by these crops. This analysis is best possible in the tropical region like Nagpur, the selected location for the present study.

Fig. 3.8: Google map location of experimental setup

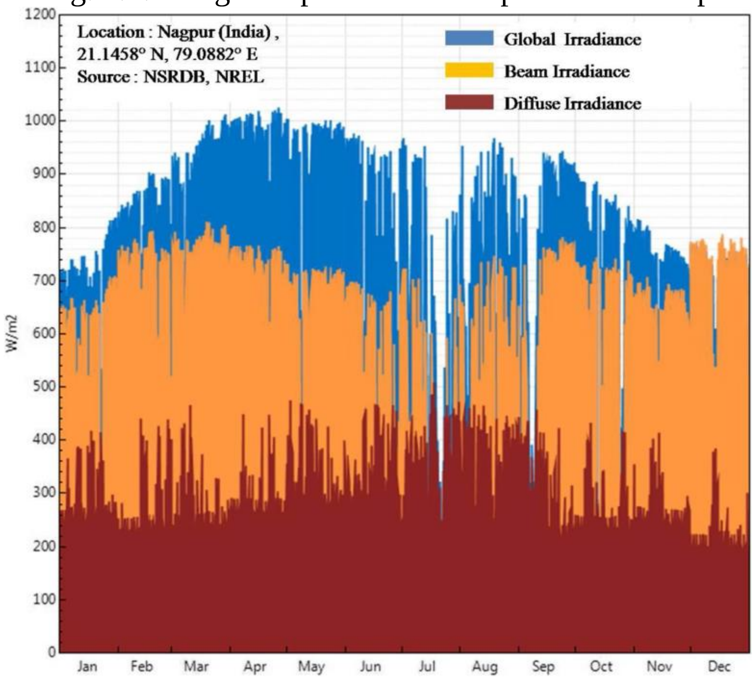


Fig. 3.9: Available solar resources at the location

- **Type of PV Plant**

The on grid and off grid photovoltaic plants are the two major categories in solar PV plant. In the present experimental study, the performance of APV power plant is to be compared with the porformance of conventional power PV plant. The effect of the crop cultivation on the power output of the PV modules is intended to study. Thus, it is essential to connect the suitable load to the PV system to measure its output for the extended period of time throught the year. Tn case of offgrid system the power output of the PV modules would have been required to store in the batteries or use in a (2 kWp) capacity live load, this seemed impractical for the experimental studies. Thus to compare the power output of conventional PV system and the APV system both the systems were connected to a common live grid. This makes the system easier to operate for prolonged time and during experimental study the substantial power has been generatedand and feed to the grid. Thus the on-grid solar PV plant without crops (conventional PV) and APV plant (with crops) was built on the same rooftop.

- **Choice of PV module**

There are several types of PV modules used in the commercial PV power plant. The most commonly used PV modules are Polycrystalline PV modules and Monocrystalline PV modules. In the present study, one of the objectives is to study the feasibility to convert the existing solar PV plant into APV plants. Thus , it was imperative to make use of such PV modules which are generally being used in most of the existing PV installations. Also, to study the effect of cooling due to cultivated crops on the performance of PV modules, the polycrystalline modules was considered as a best choice. 330 watt, polycrystalline PV module were selected. Figure 3.10 shows the selected PV modules for the experimental setup.

SOLAR PV SYSTEM MODULES	
Make	Luminious Power Technologies
Model No.	LUM24330
Capacity of each Module (Wp)	330Wp
No. of Modules	06
Total Capacity (kWp)	1.980 kWp
Cell Type	Poly
No of cells	72
Peak Power Pmax (Wp)	330
Maximum Power Voltage Vmp (V)	38.03
Maximum Power Current Imp (A)	8.68
Open circuit voltage Voc (V)	45.53
Short circuit current Isc (A)	9.22
Module efficiency (%)	16.85%
Maximum System Voltage	1000V
Maximum Series Fuse Rating	20A

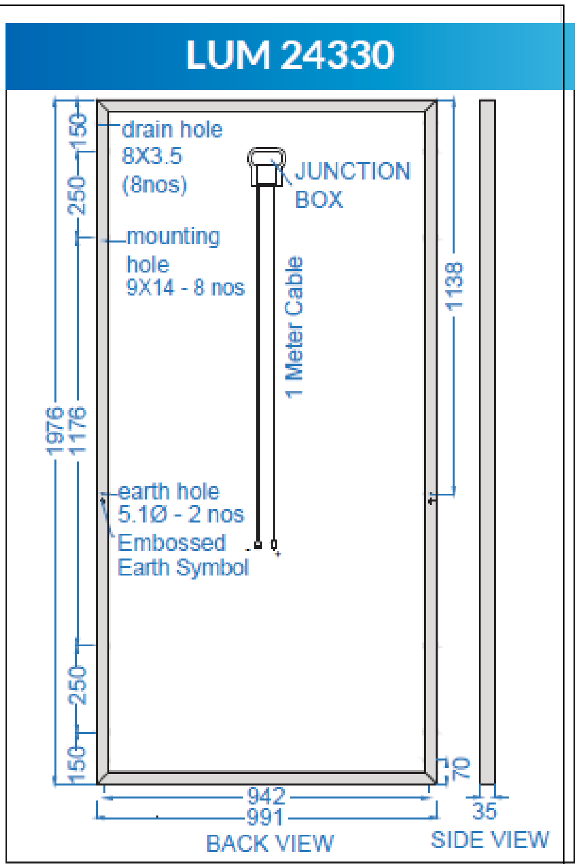


Fig. 3.10: Details of PV module for the experimental setup

- **Plant Design**

Design of the conventional and APV plant for the purpose of experimental study is one of the major tasks in the present research research study. The plants were design keeping in mind the following considerations

  - The conventional and APV power plant should have exactly same specifications.

- The mounting structure should have the provision to adjust the gap between the crops and the PV module
- The mounting structure should allow the access below PV module to cultivate the crops.
- The mounting structure should allow the access to measure the module temperature .
- The plants should have the capability to measure the output of individual plants seperately.

Considering all the above points the conventional and APV plant was designed as discussed in the subsequent paragraphs. Figure 3.11 shows the major steps in the design of conventional, APV plant and the experimental setup

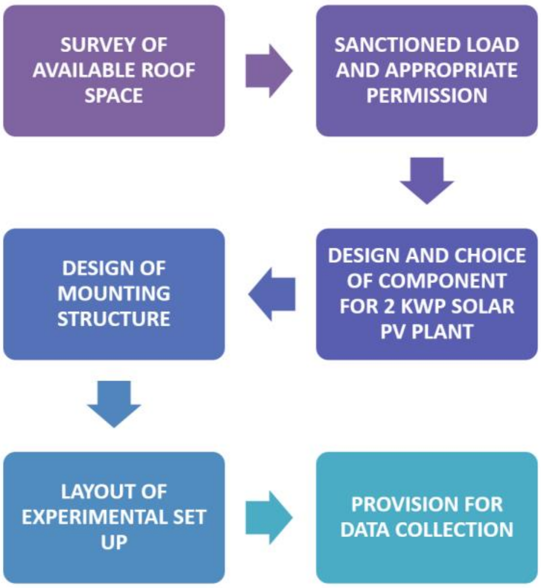


Figure 3.11 Major design steps for experimental setup

Details of all the stages as shown in figure 3.11 are discussed in the subsequent text.

- **Survey of available roof space**

The available roof space was surved for the shade free area and ease of mounting structure. The total available shade free area of around 18 m^2, out of this 6 m^2 area has been chosen for conventional PV , 6 m^2 area for the APV and 6 m^2 area for the open sky farming.

- **Sanctioned load and appropriate permission**

As the experimental set up consist of grid connected solar PV plant it was essential to take all the necessary permission from the electricity board for the installation and connection of power plant to the available grid. Based on the available grid and the sanctioned capacity a plant of 2 kWp was sanctioned. Out of this 2 kWp plant, 1 kWp was considered for conventional power generation (reference case) and the remaining 1 kWp for the APV plant.

- **Design and choice of component for 2 kWp solar PV plant**

As the capacity of the power plant was fixed for 2 kWp capacity, all the subsequent calculations for selection of appropriates components were made considering this load.

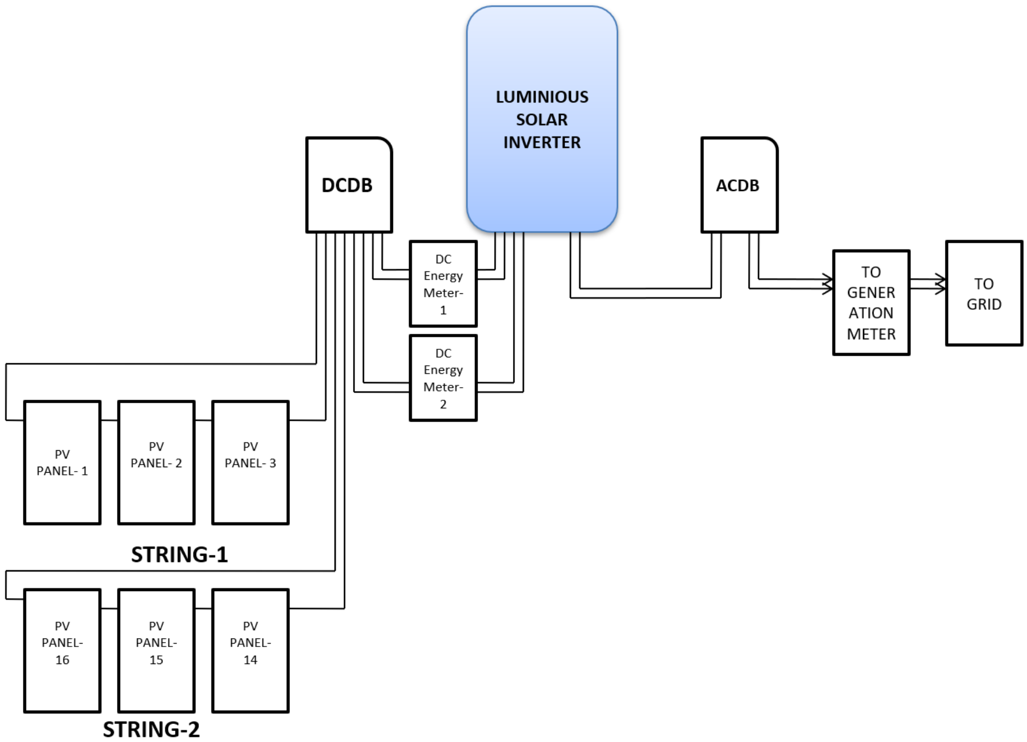


Fig. 3.12 Power plant layout with all components.

As shown in Fig. 3. 12 major components of the power plant were selected and shown in table 3.2

Table 3.2 Components used in experimental setup

Installed Inverter Details

Make	Luminious Power Technologies
Make of the inverter	LUMINIOUS
Model No.	NXI150
AC capacity of individual inverter (kW)	5 kW
No. of inverters installed	ONE
Total AC capacity of inverter (kW)	5 kW
Serial Nos.	054AC121111021 7
Single Phase	Nxi 150
Max. DC Input Power (kW)	5.8
Max. DC Input Voltage (V)	600
Start-up Voltage [V]	120
MPPT Voltage range (V)	100-500
Max input current per MPPT (A)	11A+11A
Number of MPPT	2
Max Input Strings Number	2
Rated output power (kW)	5
Max. output power [kW]	5
Max. output Current [A]	25
Grid voltage range (V)	160-285
Grid Frequency range (Hz)	50/60Hz

Power Factor (at rated output power)	0.8…1…0.8
Total harmonic distortion [THDi] < 1.5%	< 1.5%
Feed-in phase/connection phase Single Phase	Single Phase
Max. Efficiency	> 98.1%
Utility	**DC to AC convert**

DC Cables Details

Make	POLYCAB
Size & Type	4 Sq. mm
Any other information	DC Cable
Utility	**To supply DC current**

AC Cables Details

Make	KEI wires & cables
Size & Type	4 Sq. mm Three core flexible
Any other information	AC Cable
Utility	**To supply AC current**

DC Distribution Box

DC Surge Protection Device	585 V DC VALVETRAB TWO unit
Size & Type	Two 1000 V DC Fuse and Two VALVETRAB SPD unit
Any other information	For two separate strings separate Fuse and SPD are available.
Utility	**DC protection device**

AC Distribution Box

AC Surge Protection Device	VALVETRAB One unit
MCB /MCCB quantity &capacity	Schneider 2 Pole MCB 32 Ampere
Size & Type	2 Pole MCB 32 Ampere
Any other information	Two pole Schneider RCCB 40 A Fitted
Utility	**AC protection device**

- **Design of mounting structure**

The three major aspects were considered while designing the mounting structure.

a) Maximum and minimum height of the structure

b) Optimum tilt angles

c) Adjustable height for APV plant

a. The maximum and minimum height of the mounting structure were selected as per the maximum height of the full grown selected crop.

b. Equation (3.1) was used to calculate the optimum tilt angle for the installation of the Solar PV modules [11].

$$\beta(opt) = \tan^{-1}\left[\frac{\{\sum_{k=1}^{12}(H(b)\tan(\phi-\delta)\}}{\sum_{1}^{12}H(b)}\right] \qquad 3.1$$

For the location of the present experimental set up the optimum tilt is calculated as 21.1°.

c. **Adjustable height -** The structure has a made a provision to vary the mounting height so as to facilitate the different distance between crops and PV modules. The mounting structure was made up of hot dipped Galvanised Iron frames of 2 mm thickness with a square cross section of 50 x 50 mm size . The PV module are bolted to the structure. Fig. 3.13 shows the mounting structure.

Fig 3.13 Mounting structure

- **The layout of experimental set up**

After selecting all the components, mounting structure , the power plant was designed at first the plant design was made using helioscope software tool. Fig 3. 14 shows the plant layout given by the helioscope . To convert the plant into two separate segment . Out of 6 module two strings of 3 modules were made. One string was used s conventional PV plant and the others as PV plant . The scheme of the entire plant is shown in Fig. 3.15

Fig. 3.14: Design of 2kWp plant using HelioScope

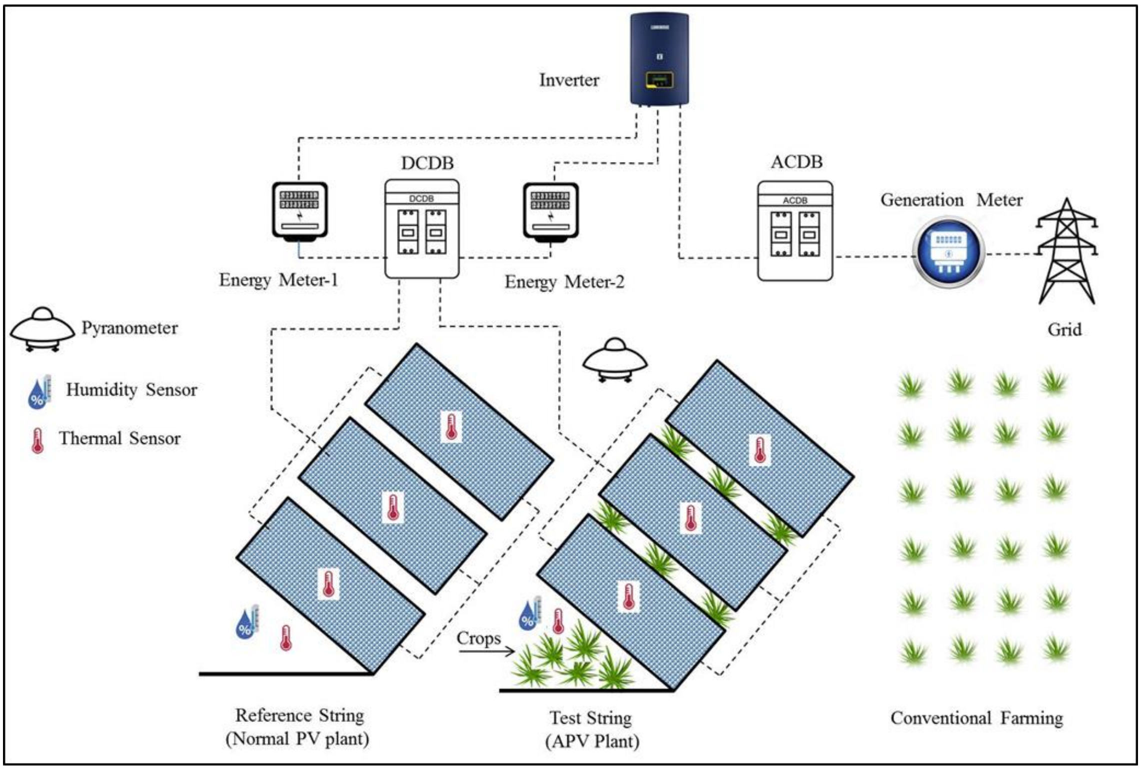


Fig.3.15: Schematic of Experimental set up

- **Provision for Data Collection**

The following parameters were measured during the experimental study.

  - DC/AC Voltage

- DC/AC current
- Power
- Units generated
- Atmospheric Temperature
- DBT, WBT
- Radiation intensity
- Surface temperature of PV module
- Plant height

The instruments used to measure the above parameters are listed in table 3.4

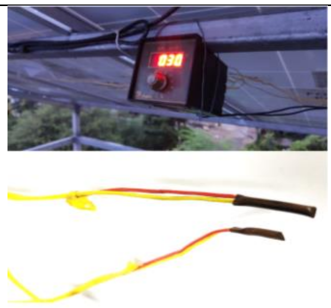
Table 3.3 Details of instruments used for experimentations

Solar radiation meter

Make	TENMARS ELECTRONICS CO. LTD.
Model No.	TM-207
Measuring Units	W/m^2 or BTU
Range	2000 Watt Per Square Meter,634 BTU
Display	Digital
Utility	**Solar irradiance**

Digital temperature indicator and thermocouples details

Make	Creative Controls
Model No.	DTI-3012
Measuring Units	ºC
Range in ºC	600 ºC
Display	Digital
Input Type	Thermocouple (12 Inputs)
Thermocouple Type	J Type (0 to 750ºC)



Utility	**Module Temperature**

Digital Infrared Thermometer

Make	Fluke
Model No.	59 Max+
Measuring Units	ºC
Range in ºC	-30 ºC to 500 ºC
Display	Digital
Spectral Response	8-14 µm
Thermocouple Type	J Type (0 to 750ºC)
Utility	**Module Temperature**

DC Energy Meter

Make	Everon Energy Systems Pvt. Ltd.
Model No.	EV-DSL-01D
Display Parameters	Voltage, Current, kW-h Previous Day & kW-h Present Day
Voltage Range	0-300 V DC
Current range	0-40 A DC
Display	Digital
Standard Accuracy	+/-1%
Utility	**Voltage, Current, Power, Generated Units**

Psychrometer

Make	Omsons
Display Parameters	Dry Bulb & Wet Bulb Temperature
Temperature Range	-10 to 50^{O}C
Utility	**Dry and Wet Bulb Temperature**

Pocket **Measuring Tape**

Make	Freemans
Display Parameters	Length
Range	0 - 5 meters
Utility	**Dry and Wet Bulb Temperature**

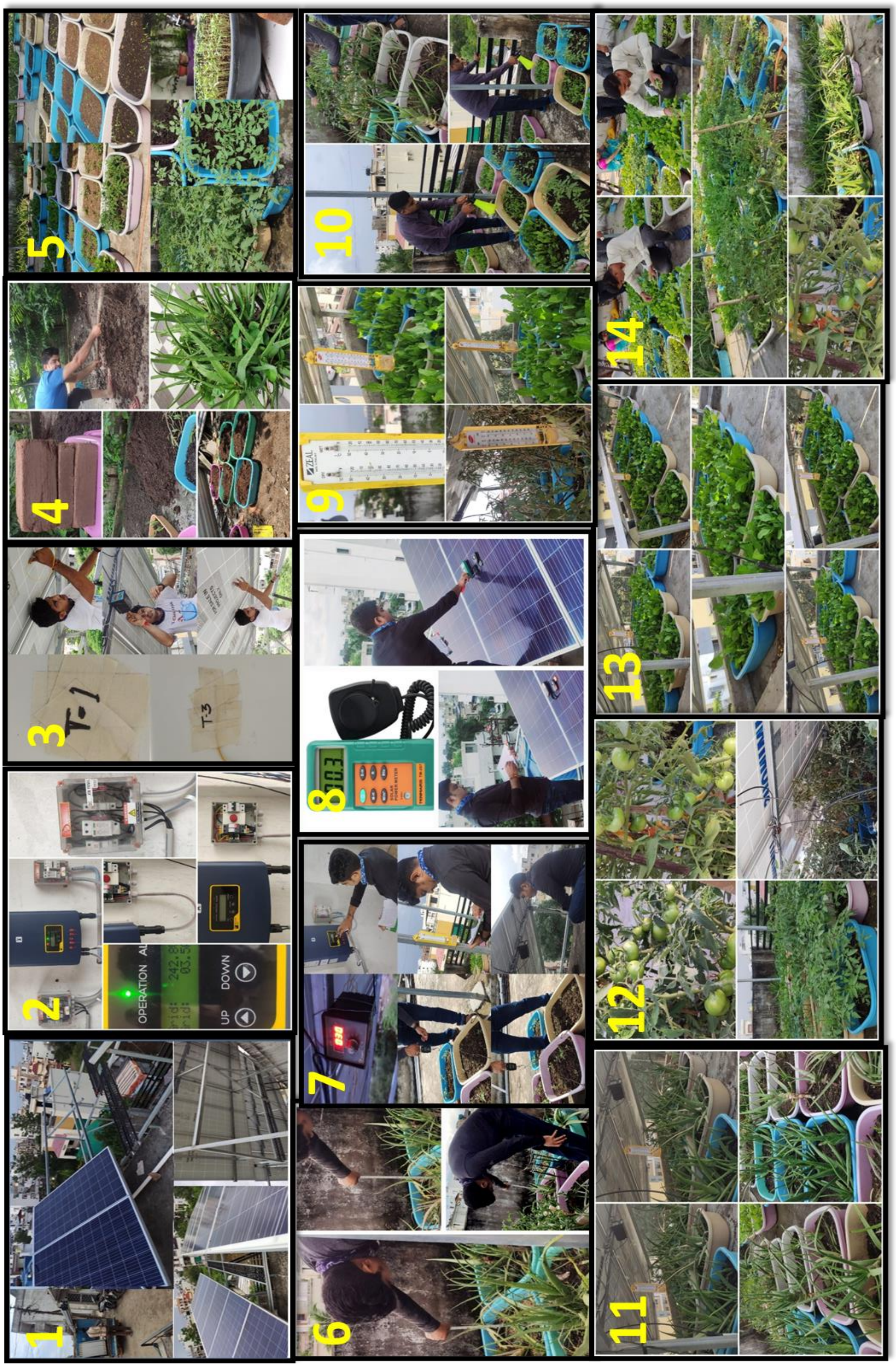


Fig. 3.16: Actual photographs of the complete experimental facilities.

In Fig. 3.16, the numbers denote

1. Installation of module mounting structure and PV panels
2. Installation of inverter, ACDB, DCDB & energy meters
3. Installation of Thermocouples & Digital temperature indicator
4. Preparation of Tubs for cultivation of Crops
5. Cultivation of Spinach, Tomato & Aloe Vera under open sky
6. Measurement of plant growth
7. Measurement of PV module temperature, current, voltage, etc.
8. Measurement of solar radiation
9. Measurement of DBT & WBT
10. Watering and nourishment of crops
11. Cultivation of Aloe Vera below PV modules
12. Cultivation of Tomato below PV modules
13. Cultivation of Spinach below PV modules
14. Harvesting the crops

Chapter-4

Experimental Investigations

This chapter presents the precise details of the experimental studies and findings from the experiments conducted with the developed experimental setup. The experimental study primarily reports the effect of different crops, the height of the crops, and their impact on the electrical and thermal performance of the PV modules.

4.1 Details of experimental studies

The experimental setup, as mentioned in chapter 3, consists of an open sky farm, a conventional 1 kW solar PV plant without any crops, and a 1 kW APV system. It has been ensured that the system is completely ready for operating correctly and safely for the recording of various parameters.

The experiments were planned to study the following aspects

i. Crop growth in open sky conventional farming and in the APV system
ii. Effect of cultivation on the microclimate beneath the PV module
iii.Effect of cultivation on PV module temperature
iv.Effect of module temperature on the power generation
v. Effect of different crops on the APV plant performance
vi. Effect of different heights of the crops on the APV performance

In the experimental studies, radiation intensity, surface temperature of the PV modules, ambient temperature, humidity, crop growth, energy generated by each string and the complete plant were measured. The respective instruments were used to measure the experimental data as mentioned in table 3.3 (chapter 3, section 3.1.5) The power generation from the two strings was measured using two separate DC energy meters and the combined output was measured using a string inverter.

To study the aforementioned aspects, a systematic experimental study was planned as shown in fig.4.1.

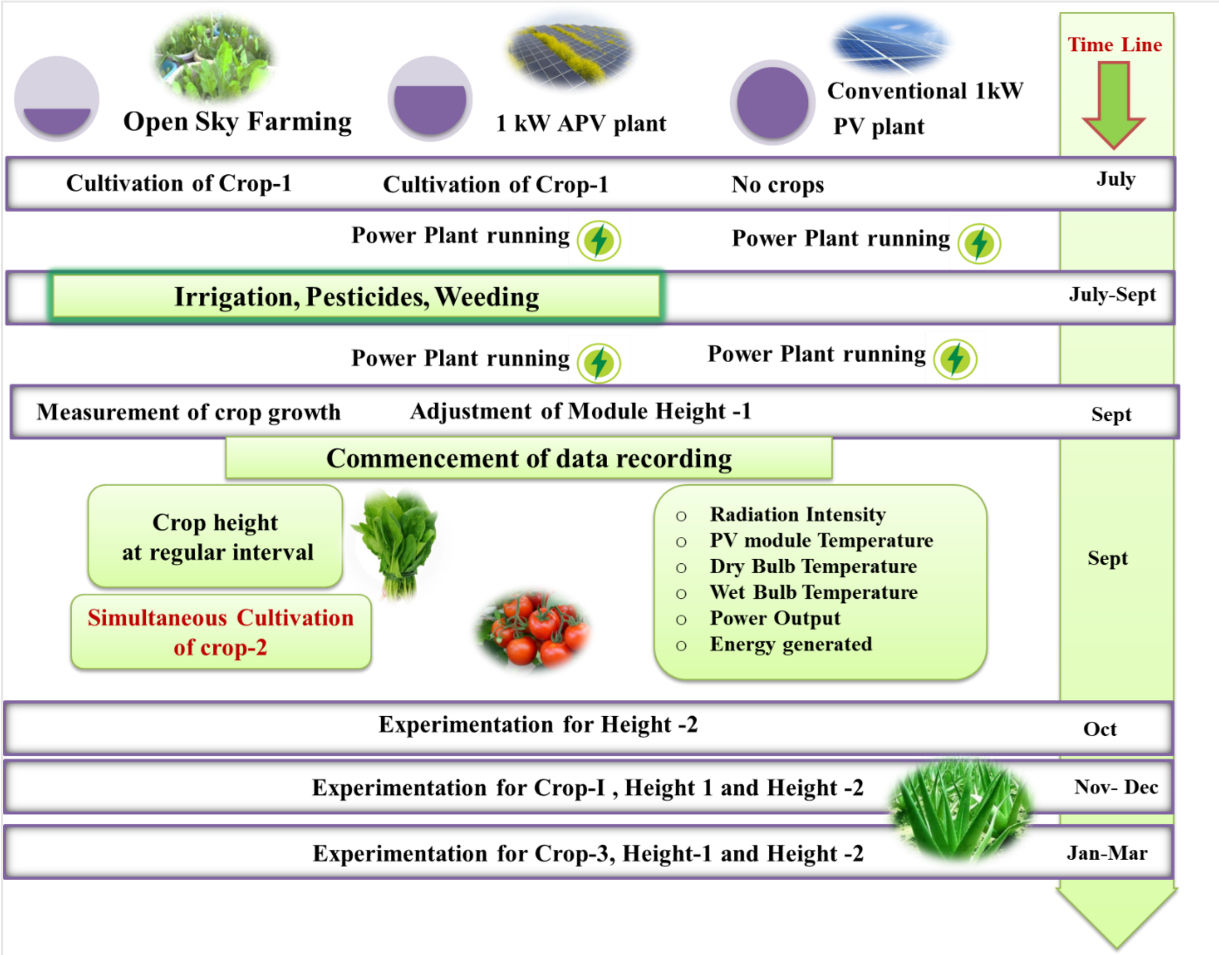


Fig 4.1. Experimental study

The fig. 4.1 shows the entire process of the experimental study, in fig. 4.1 time line indicates the months of the activity, and the horizontal lines indicates the major activity carried out during the experimental study. The experiments were divided into three major phases as shown in table 4.1

Table 4.1: Selected crops for APV systems

Sr. No.	**Name of Crop**	**Condition**	**Period of cultivation**	**Period of data collection**
Phase-I	Aloe vera	Height-1 (1m)	July – September	September
		Height-2		October

		(1.5m)	3 Months	
Phase-II	Tomato 	Height-1 (1m)	Sept – November 3 Months	November
		Height-2 (1.5m)		December
Phase-III	 Spinach	Height-1 (1m)	Dec-January 2 months	January
		Height-2 (1.5m)		Feb- March

The major steps carried out during the entire study as shown in fig. 4.1 and table 4.1 have been elaborated in as step by step procedure in section 4.2 as below.

4.2 Procedure followed for the experimental study

The following procedure was adopted for the experimental study

- As discussed in chapter 3, the experimental set up consists of open sky farm, conventional PV power plant of capacity 1kWp and the same capacity APV power plant. The experimental set up was designed so carefully that, the two power plants are of exact same specifications and are connected to a common grid using a single grid tied inverter. Also, the mounting structure of the power plant was designed keeping in mind the requirement to vary the height of the structure to investigate the effect of crop height in the APV system.

- As discussed in chapter 3, section 3.1.4, fig. 3.5, the necessary preparation for the cultivation of crop in open sky and APV farming was made.
- Aloe Vera was selected as the first crop for the experimental study, the saplings of the crop were cultivated in the 16 trays in the month of July.
- Out of those 16 trays, 10 number of trays were shifted below the APV plant and remaining 6 trays were placed in the selected shade free space (hereafter named as open sky farm). The trays were numbered as Tray S01, S02 and so on.
- The crops were maintained from July to September by proper irrigation, weeding, pesticide and fertilizers.
- During this period, the proper functioning of the APV plant and the conventional PV plant was ensured by observing the electrical parameters of the plants. The plants were running and generating the substantial amount of electricity and feeding it to the grid.
- The growth of the crops in both APV system and the open sky farm was monitored using measuring tape at regular interval of time as shown in fig. 4.2.

Fig. 4.2: Measurement of crop growth

- The crop growth was comparable in both the cases, as soon as the crop reaches 10 inch of height (in the first week of September) the observation of electrical and thermal performance of the power plants were started in Phase I.
- In phase I, at first the height of PV modules in APV plant was adjusted to 1 M from the ground, keeping the gap between the crop 1 and the PV module as 0.75 m as shown in fig. 4.3., Fig. 4.4 (a) & Fig. 4.4 (b) shows the Aloe vera crops cultivated in below PV module APV system and in open sky farm.

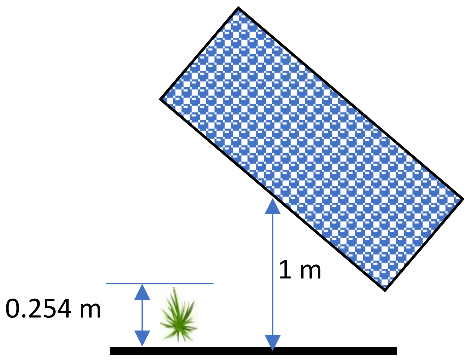


Fig. 4.3: Height of crops in APV system Phase-I

Fig. 4.4: Experiments Phase-I with Aloe Vera crops

- After adjusting the height of the PV modules in APV system, the electrical and the thermal parameters of the conventional and APV system were recorded for the entire day for the period of one month (September).
- The day of experiment starts with cleaning of PV modules, checking of wiring connections, checking of proper function of inverters by measuring the E-day readings of power generation, string voltage and current.
- For the electrical performance of the system, it was essential to investigate the performance of each individual string of 1 kWp (i.e one string of 3 PV modules as conventional power plant and one string of 3 PV modules as APV plant). For this purpose, two separate DC energy meters were attached to the two strings before the inverter. (The details are already explained in chapter 3)
- The electrical performance of the system includes the observation of
    - Instantaneous DC voltage of conventional and APV plant
    - Instantaneous DC current generated by conventional and APV plant
    - Instantaneous power generated by the conventional and APV

plant

- Electrical units generated per day by conventional and APV plant

All these parameters were measured by two different instruments viz; the DC meter and grid tied inverter. Fig. 4.5 & Fig. 4.6 shows a sample observation showing the measurement of Electrical units generated per day by conventional and APV plant by both these instruments in string-I and string-II respectively

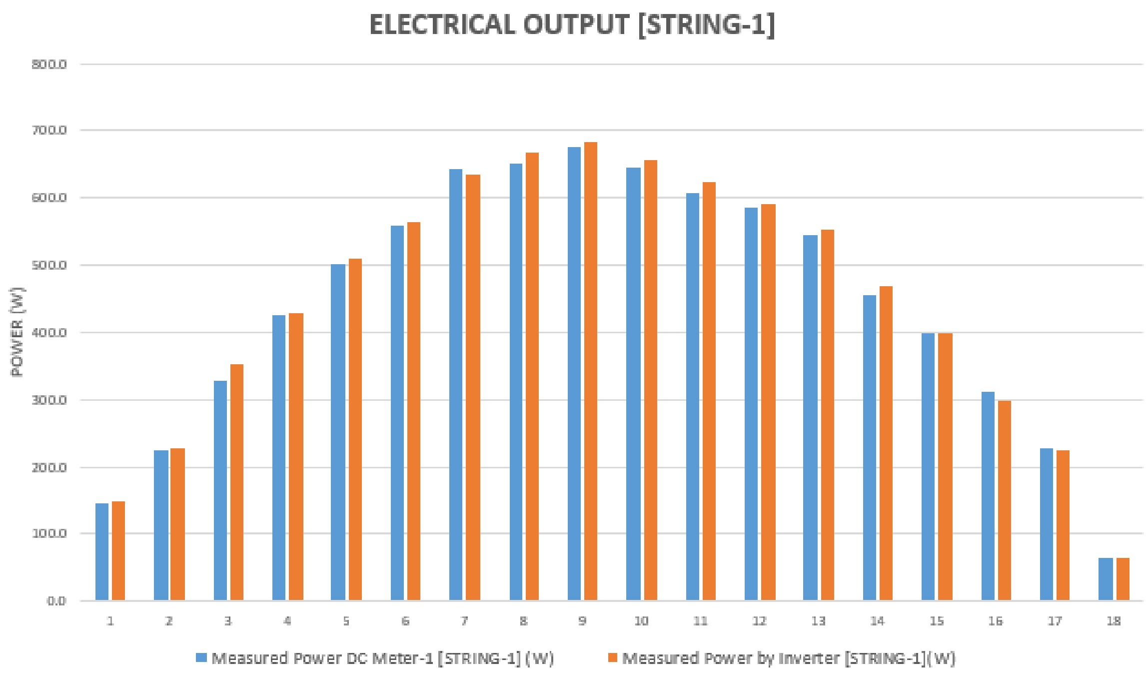


Fig.4.5: PV measured output [String-1]

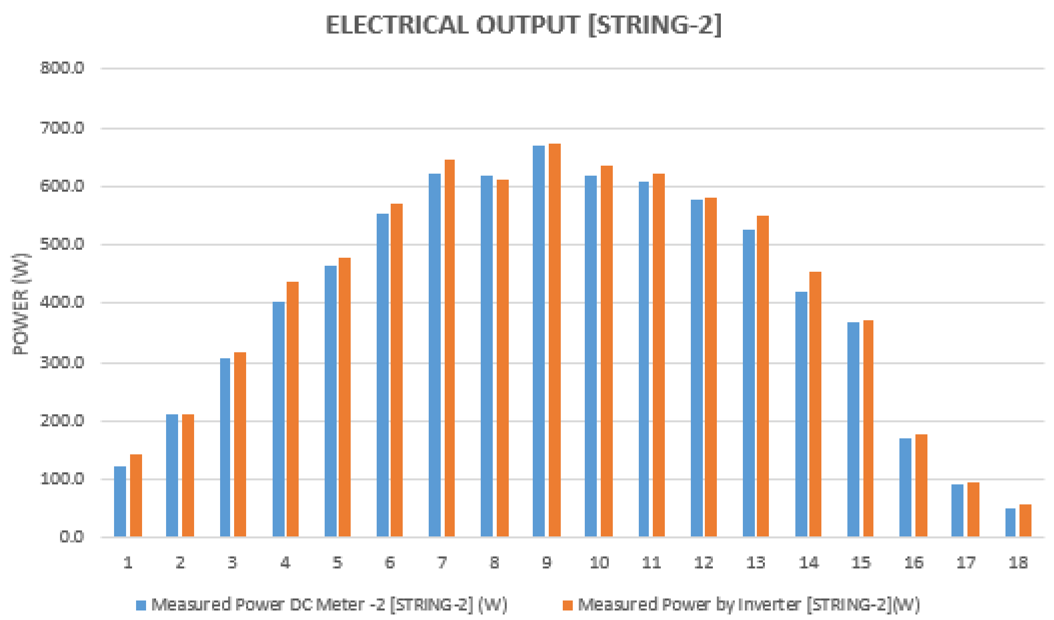


Fig. 4.6: PV measured output [String-2]

As shown in fig. 4.5 & Fig. 4.6, the variations in both the measurement are negligible thus, the measurement of DC meters were considered in the subsequent calculations.

- In the thermal performance investigations, the following parameters were measured
  - PV module temperature in both conventional and APV system
  - Dry bulb temperature below the PV modules of conventional and APV system
  - Wet bulb temperature below the PV modules of conventional and APV system
  - Ambient temperature
  - Dry bulb and wet bulb temperature of the atmosphere
  - Radiation intensity (Global irradiance) on the plane of PV modules

- For measurement of the temperature of the PV modules, two digital temperature indicators of 12 input ports and in total 12 thermocouples were used. The thermocouples were fixed to the solar PV module using appropriate thermal adhesive tape as shown in fig. 4.7

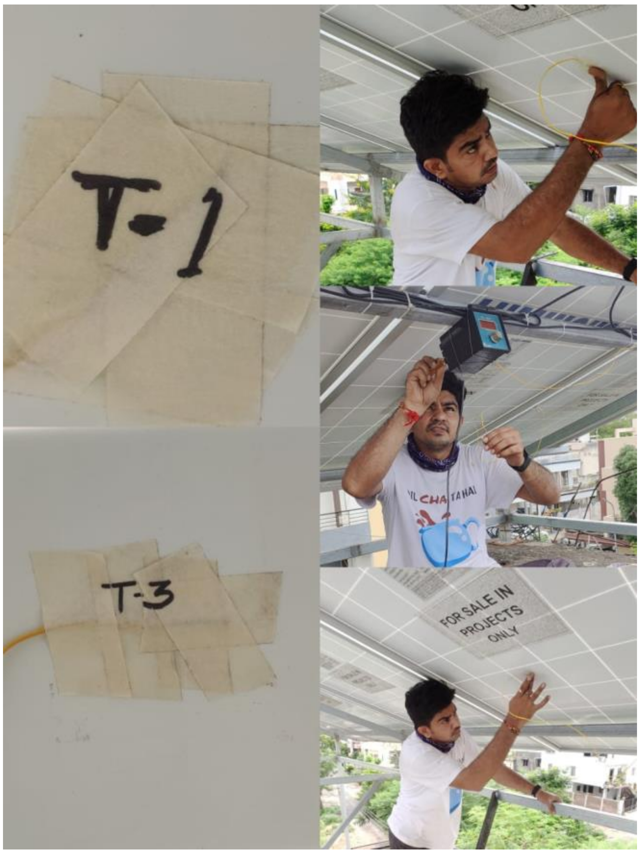


Fig 4.7: Measurement of PV module temperatures

- Dry bulb and wet bulb temperatures at three spaces viz; ambient, below the PV module in conventional power plant, below the PV module in APV plant were observed using three separate Sling Psychrometers as shown in fig. 4.8.

Fig. 4.8: Measurement of DBT and WBT

- The irradiance was measured using the solar meter at the plane of installed PV modules as shown in fig.4.9

Fig. 4.9: Measurement of irradiance using solar meter

- All of the aforementioned parameters were recorded after every 30 minutes of the experiment, which had an average experiment day starting at 8 AM and ending at 4:30 PM each day.

- During this time the activities like irrigation, weeding, fertilizers, pesticides were continued to APV farm and the open sky farm.

- In addition, there were no interruptions in the power plant's ability to produce electricity, and each of the strings generated a sizable amount of power—roughly 4 to 5 kWh every day.

- A sample of the observed data for the Crop-1 for height -1 (Aloe Vera with Height -1) is shown in table 4.2.

Table 4.2: Sample observations for Crop-1, Height -1

TIME	D. C. METER-1/ STRING-1 (APV)				D. C. METER-2/STRING-2 (Conv.)				TEMPERATURE						SOLAR RADIATI ON	PV MODULE TEMPERATURE (ABOVE)						PV MODULE TEMPERATURE (BELOW)					
									1. Atmospheric		3. Agrovoltaics		2. Conventional			APV			CONVENTIONAL			APV			CONVENTIONAL		
	Voltage (V)	Current (A)	Power (W) APV	Units (Kw-h) APV	Voltage (V)	Current (A)	Power (W) Conventional	Units (Kw-h) Conventional	DBT (oC) Atmo.	WBT (oC) Atmo.	DBT (oC) APV	WBT (oC) APV	DBT (oC) Conventional	WBT (oC) Conv.		T-1	T-2	T-3	T-14	T-15	T-16	T-1	T-2	T-3	T-14	T-15	T-16
8:00 AM	106.2	3.3	351.7	0.1	107.8	3.0	321.3	0.1	24.0	19.0	20.0	17.0	20.0	16.0	208	17.7	18.3	18.2	16.6	20.0	20.1	23.2	21.4	23.2	27.3	26.8	27.4
8:30 AM	106.1	4.1	440.1	0.3	107.8	3.8	407.5	0.2	26.0	19.0	20.0	18.0	22.5	16.5	303	21.1	21.8	22.1	22.9	24.5	23.5	27.5	27.2	22.7	29.8	30.5	31.4
9:00 AM	108.6	5.0	538.6	0.5	110.6	4.5	500.8	0.3	28.0	20.0	21.0	18.0	23.0	17.0	455	24.9	25.4	26.3	27.7	28.8	27.5	31.0	33.0	31.7	39.8	36.0	35.1
9:30 AM	106.4	5.8	614.1	0.6	110.1	5.2	574.1	0.4	29.0	21.0	22.0	19.0	25.0	17.0	578	27.0	28.7	29.0	29.6	30.5	29.5	35.6	36.5	35.6	38.5	39.3	38.5
10:00 AM	100.1	6.8	680.1	1.0	103.5	6.1	636.5	0.7	31.0	21.0	22.5	20.0	25.5	18.0	684	31.1	32.1	32.3	33.5	33.3	32.2	39.0	40.3	38.5	43.5	44.1	43.1
10:30 AM	104.2	7.0	730.0	1.2	102.6	6.7	683.9	0.9	30.0	21.0	23.5	20.0	26.0	18.0	973	32.8	33.3	32.8	35.8	34.8	34.3	40.0	40.3	40.3	44.5	44.2	44.5
11:00 AM	104.2	7.4	767.4	1.9	105.4	6.8	715.4	1.4	31.0	22.0	25.0	21.0	27.0	19.0	884	37.5	37.7	39.1	38.2	28.0	38.5	44.8	44.6	44.2	47.5	47.8	48.1
11:30 AM	100.2	7.8	779.8	2.1	99.3	7.3	726.6	1.6	32.0	21.5	26.0	21.0	27.5	19.0	908	36.5	35.9	37.2	37.9	37.4	37.7	45.1	46.0	45.1	47.1	48.8	48.1
12:00 PM	101.2	7.8	787.3	2.5	104.5	7.0	734.9	2.0	32.0	22.0	26.5	21.0	28.0	19.0	936	38.8	37.6	38.5	38.9	39.7	39.7	46.5	46.5	46.3	51.8	52.4	51.3
12:30 PM	101.2	7.7	777.0	2.7	101.2	7.1	722.9	2.1	34.0	22.0	27.0	21.0	28.5	19.5	946	40.7	40.8	38.1	40.4	42.0	43.2	46.9	44.6	44.5	50.2	50.1	50.8
1:00 PM	103.2	7.3	754.5	2.9	103.1	6.8	698.3	2.5	35.0	22.0	27.5	21.0	29.0	20.0	895	39.5	40.1	38.1	39.6	40.6	40.7	45.8	45.2	45.4	49.8	51.0	48.3
1:30 PM	100.4	7.1	716.2	3.4	101.2	6.5	657.8	2.9	35.0	22.0	28.0	21.0	29.0	20.0	795	39.5	38.7	39.4	40.5	39.9	39.9	46.0	47.1	47.1	50.6	50.9	50.0
2:00 PM	99.3	6.7	665.2	3.9	103.1	5.9	610.9	3.2	35.0	22.0	28.5	21.0	30.0	20.0	755	38.3	39.6	38.8	38.8	38.5	36.9	43.2	43.4	43.2	47.3	47.5	47.2
2:30 PM	106.2	5.7	607.1	4.1	109.2	5.0	548.4	3.4	34.0	22.0	28.0	20.0	29.0	19.0	597	32.3	31.9	33.0	34.1	33.6	34.2	37.7	37.4	36.1	43.5	43.1	43.1
3:00 PM	104.2	5.1	528.8	4.3	107.2	4.4	475.5	3.8	33.0	21.5	27.0	21.0	28.0	19.0	538	32.1	34.3	32.9	33.7	33.8	34.4	39.4	40.0	39.9	43.3	43.2	43.4
3:30 PM	100.2	4.3	433.2	4.5	113.4	3.5	391.8	3.9	31.0	21.0	27.0	20.0	28.0	19.5	366	3.1	29.9	30.0	30.0	30.6	30.9	32.8	31.9	32.1	40.0	38.3	38.7
4:00 PM	102.5	3.2	329.5	4.7	119.7	2.5	296.0	4.1	29.0	20.5	26.5	20.0	27.0	19.0	275	27.5	27.9	28.0	27.9	27.6	28.6	33.8	31.1	30.1	36.1	35.9	36.1
4:30 PM	104.2	2.1	220.3	4.9	116.7	1.6	189.6	4.2	28.0	20.5	26.0	20.0	26.5	19.0	200	24.0	24.2	23.1	23.0	25.1	25.4	30.8	26.8	27.7	32.8	33.0	33.6

- After completion of crop 1, height-1 observations, in the next month the height -2 (i.e module height of 1.5 m from the ground) was set.
- And the same procedure was followed for the period of next one month. This ends the Phase-I of experiments from July- October, a period of 4 months. The full-grown Aloe Vera after the Phase I experiments get over are shown in fig. 4.10. The growth of aloe vera in conventional and APV was comparable.

Fig. 4.10: Growth of Aloe Vera after Phase-I of experiments

- For Phase II, again the height of the PV module in APV plant was lowered to height -1 (i.e. module height of 1 m from the ground) of the experiments another crops i.e. Tomato was selected, which was cultivated in the month of September in both open sky and APV system. The growth of the crops was recorded regularly and as soon as the crop reaches to around 0.3m height the observations for Phase -II were started in the month of November.
- While growing the Tomato plant it was necessary to support the plant by using the suitable stakes, thus the bamboo stakes were used to keep the plant upright as shown in fig. 4.11. Fig. 4.11 (a) & (b) shows the Tomato crops cultivated in below PV module APV system and in open sky farm

Fig 4.11: The phase-II experiments with Tomato Crops

- The same procedure as that of Phase-I was repeated for Tomato crop for Height 1 and Height 2 till the month of December. Thus, the Phase-II of experiments were executed from the month of September to December.
- For the Phase-III of experiments, the third crop i.e. Spinach was cultivated in the month of December, the observation for Phase-III were started as the height of the Spinach reaches to 0.1 m. The same procedure was adopted to investigate the performance of the APV system with Spinach crop. This phase III of experiments were last till the month of March.

Fig 12: The phase-III experiments with Spinach Crops

- Thus, in overall the entire experimental study was executed from the month of July to March.

The significant observations from the experimental study have been discussed in the subsequent text.

4.3 Performance Investigations of Conventional PV and APV system

Following the above-mentioned extensive and systematic experimental studies, the performance of the APV system in comparison with the conventional PV power plant was analyzed. The analysis is based on the experimental data captured for around 273 days (6552 hours) in the different seasons of the year with different crops. The subsequent sections describe the findings of each of the study in detail.

4.3.1 Performance investigations of APV system for Aloe Vera for Height-I

The performance of the conventional PV system and the APV system with Aloe Vera crop by maintain the module height as 1 m from the ground has been explained in the below text.

4.3.1.1 Growth of Aloe Vera

The growth of the Aloe vera plant in both open sky farm and below the PV modules in APV system was recorded. Fig. 4.13 shows the comparison between the growth of Aloe vera crop in open sky and in APV system respectively.

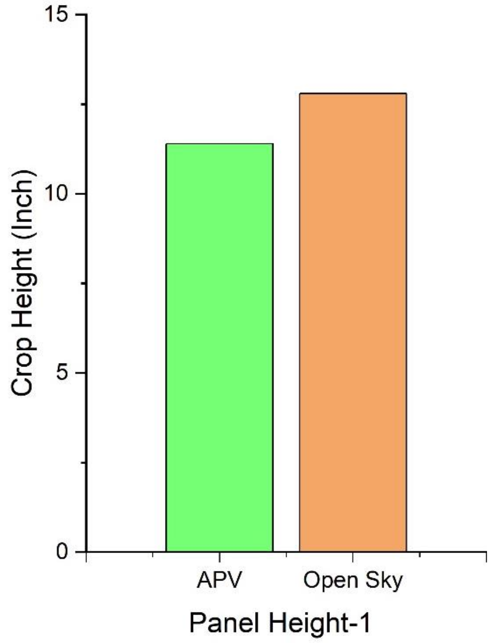


Fig. 4.13: Growth of Aloe Vera in open sky and in APV

As shown in fig. 4.13, the growth of the Aloe Vera plant in case of open sky farming was around 12.8 inch whereas in the APV it was 11.4 inch over the period of experimentation. Thus, it can be seen that the average growth of Aloe Vera in case of APV system is slightly lower as compared with the conventional open sky farming.

4.3.1.2 Temperature below PV module

The crops cultivated below the PV modules in the APV system contributes in reduction of the temperature below the PV module. This was evident from the observed data as shown in fig 4.14.

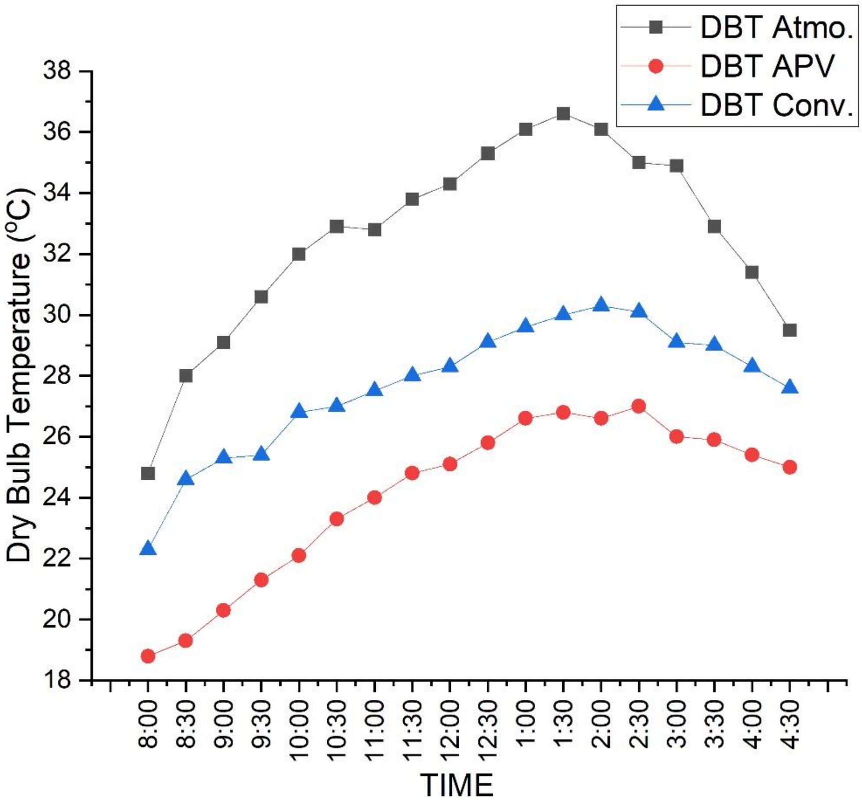


Fig. 4.14: Temperature below PV modules for Aloe Vera Height-1

The average ambient temperature is always higher than the temperature below the PV modules, as shown in fig. 4.14. The temperature below the PV module in an APV system is lower than both the ambient temperature and the temperature below the PV module in conventional PV system, as shown by Fig. 4.14. Further, it has been observed that in an APV system, the temperature below the PV module for Aloe Vera crop with a module height of 1 m was found largely to be 11.16% lower as compared with the conventional PV power plant.

4.3.1.3 Temperature of PV modules

The temperature of the PV modules was recorded in both conventional and APV system, the average values of temperatures for Aloe Vera crop for Height of module as 1 m are shown in fig. 4.15.

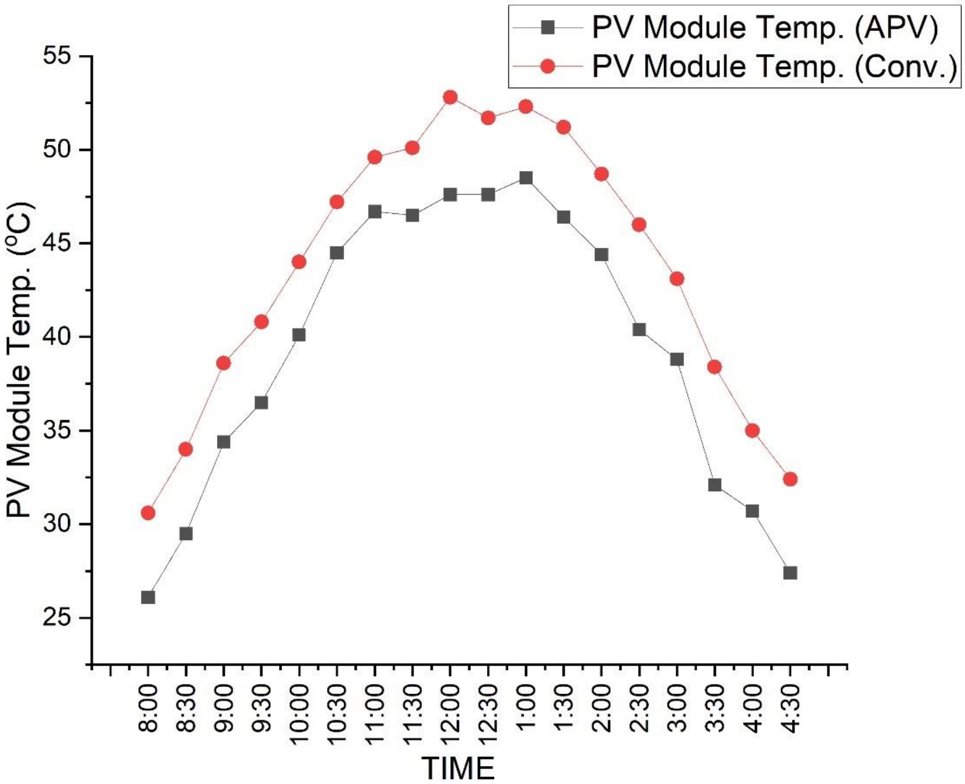


Fig. 4.15: Temperature of PV modules for Aloe Vera Height-1

The temperature of the PV modules in the APV system is always lower than the temperature of the PV modules in the conventional PV power plant, as shown in fig. 4.15. When compared to the PV module temperature in the conventional power plant, the average PV module temperature in APV system for the Aloe Vera crop in Height - I was about 11.12% lower.

4.3.1.4 Power Output of the PV module

The present investigation clearly demonstrated the well-known fact that as the temperature of the crystalline PV module decreases, the power output from the PV module increases. The temperature of the PV module in APV system reduces as compared with the temperature of PV modules in the conventional Power plant. The power output of the APV system in the with the same capacity was higher than the power output of the conventional PV power plant, as illustrated in Fig. 4.16.

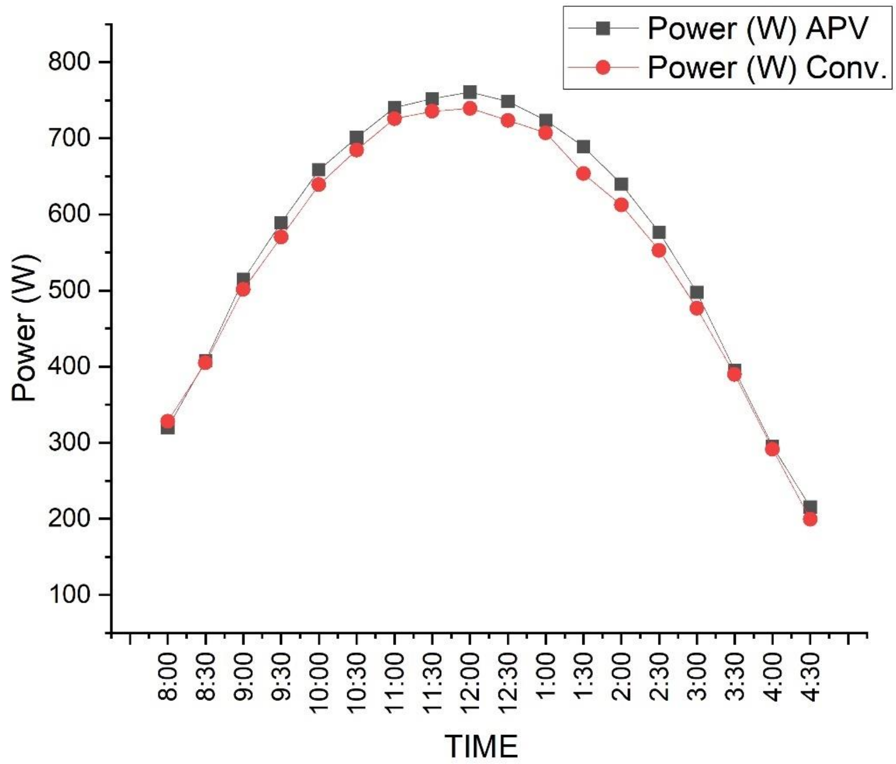


Fig. 4.16: Power output of PV plant for Aloe Vera, Height-1

As seen in fig. 4.16, the power output of an APV system is always greater than the power output of a conventional PV power plant. According to the current experimental investigations, the power output of the APV system was 7.7% higher than the power output of the conventional PV power plant.

4.3.2 Performance investigations of APV system for Aloe Vera for Height-II

The performance of the conventional PV system and the APV system with Aloe Vera crop by maintain the module height as 1.5 m from the ground has been explained in the below text.

4.3.2.1 Growth of Aloe Vera

The growth of the Aloe vera plant in both open sky farm and below the PV modules in APV system was recorded. Fig. 4.17 shows the comparison between the growth of Aloe vera crop in open sky and in APV system respectively.

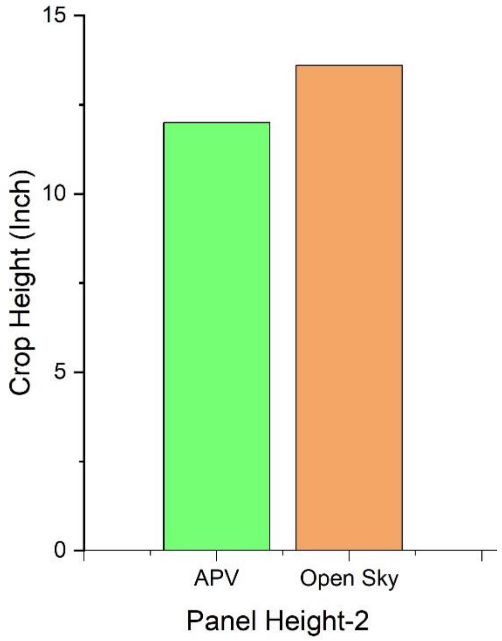


Fig. 4.17: Growth of Aloe Vera in open sky and in APV

As shown in fig. 4.17, the growth of the Aloe Vera plant in case of open sky farming was around 13.6 inch whereas in the APV it was 12 inch over the period of experimentation. Thus, it can be seen that the average growth of Aloe Vera in case of APV system is slightly lower as compared with the conventional open sky farming.

4.3.2.2 Temperature below PV module

The crops cultivated below the PV modules in the APV system contributes in reduction of the temperature below the PV module. This was evident from the observed data as shown in fig 4.18.

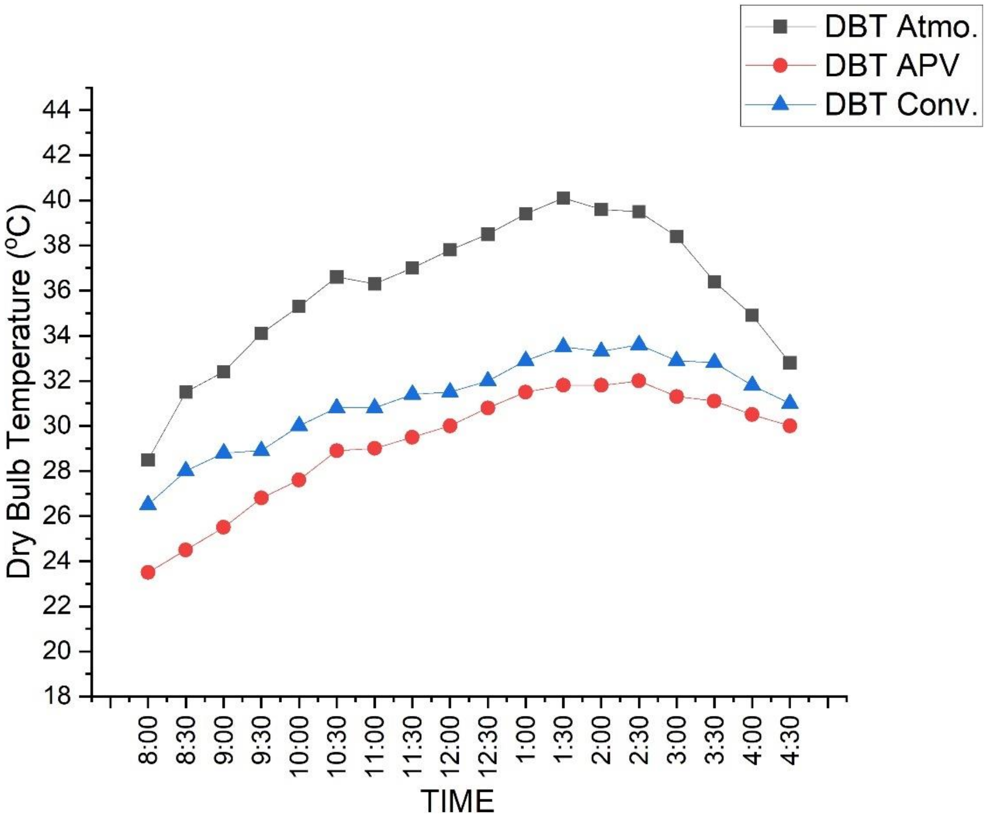


Fig. 4.18: Temperature below PV modules for Aloe Vera Height-II

The average ambient temperature is always higher than the temperature below the PV modules, as shown in fig. 4.18. The temperature below the PV module in an APV system is lower than both the ambient temperature and the temperature below the PV module in conventional PV system, as shown by Fig. 4.18. Further, it has been observed that in an APV system, the temperature below the PV module for Aloe Vera crop with a module height of 1.5 m was found largely to be 10.96% lower as compared with the conventional PV power plant.

4.3.2.3 Temperature of PV modules

The temperature of the PV modules was recorded in both conventional and APV system, the average values of temperatures for Aloe Vera crop for Height of module as 1.5 m are shown in fig. 4.19.

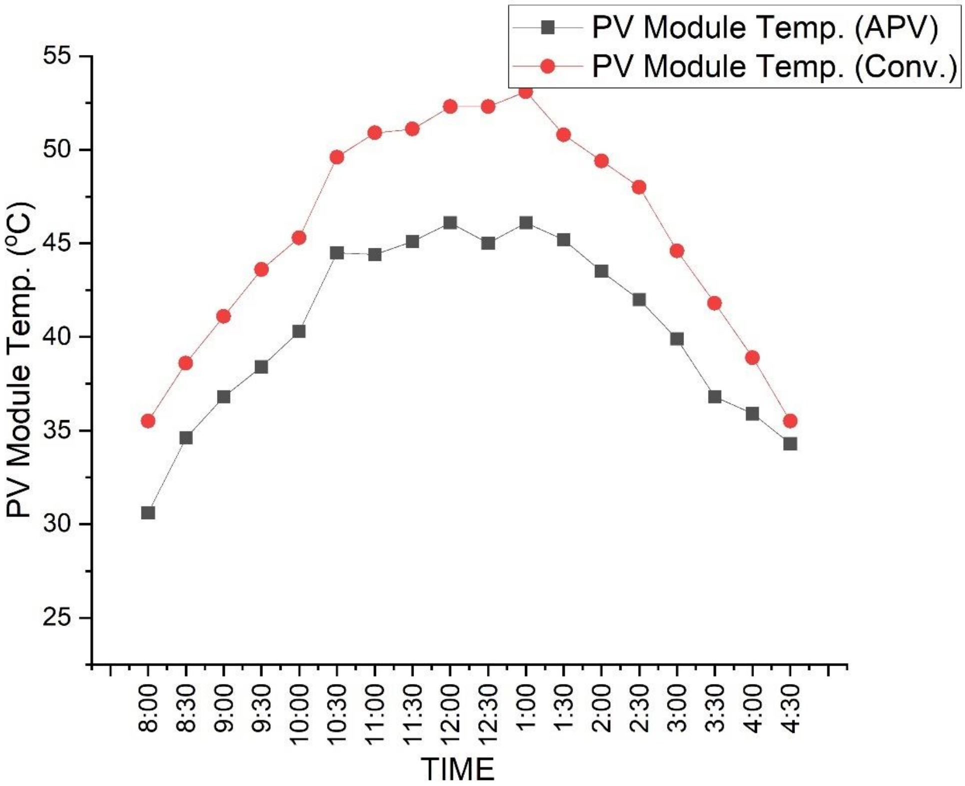


Fig. 4.19: Temperature of PV modules for Aloe Vera Height-II

The temperature of the PV modules in the APV system is always lower than the temperature of the PV modules in the conventional PV power plant, as shown in fig. 4.19. When compared to the PV module temperature in the conventional power plant, the average PV module temperature in APV system for the Aloe Vera crop in Height - II was about 12.75% lower.

4.3.2.4 Power Output of the PV module

The present investigation clearly demonstrated the well-known fact that as the temperature of the crystalline PV module decreases, the power output from the PV module increases. The temperature of the PV module in APV system reduces as compared with the temperature of PV modules in the conventional Power plant. The power output of the APV system in the with the same capacity was higher than the power output of the conventional PV power plant, as illustrated in Fig. 4.20.

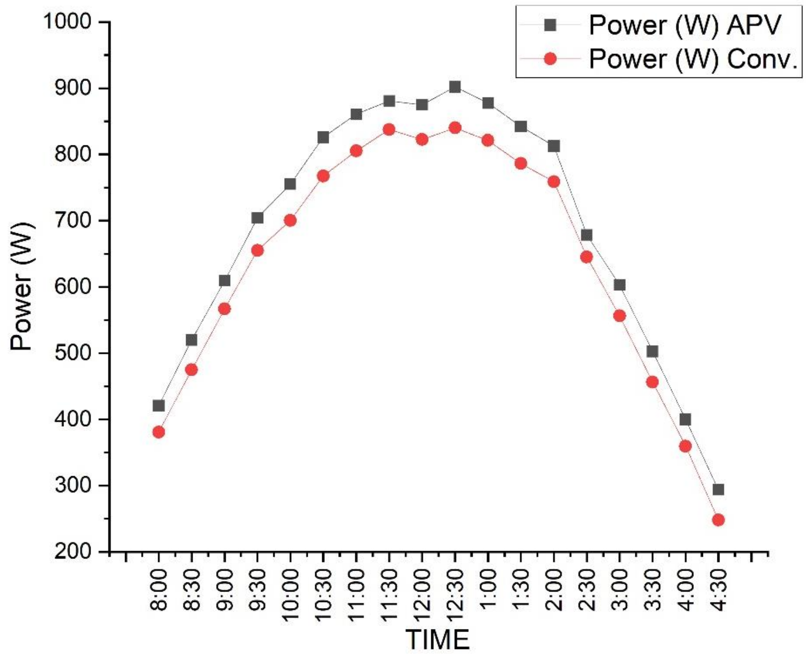


Fig. 4.20: Power output of PV plant for Aloe Vera, Height-II

As seen in fig. 4.20, the power output of an APV system is always greater than the power output of a conventional PV power plant. According to the current experimental investigations, the power output of the APV system was 7.12% higher than the power output of the conventional PV power plant.

4.3.3 Performance investigations of APV system for Tomato for Height-I

The performance of the conventional PV system and the APV system with Tomato crop by maintain the module height as 1 m from the ground has been explained in the below text.

4.3.3.1 Growth of Tomato

The growth of the Tomato plant in both open sky farm and below the PV modules in APV system was recorded. Fig. 4.21 shows the comparison between the growth of Tomato crop in open sky and in APV system respectively.

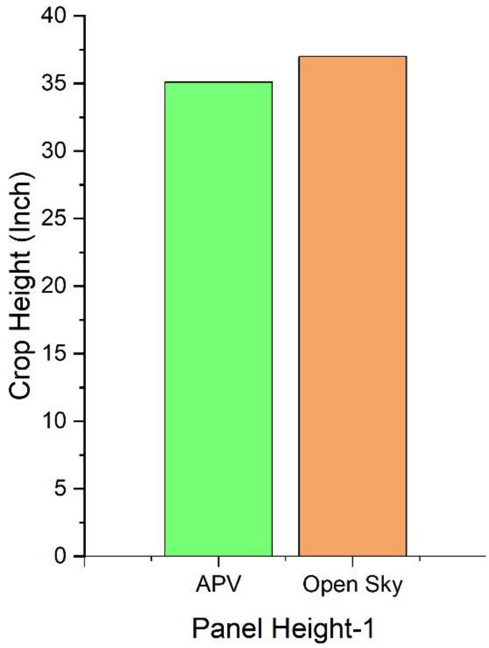


Fig. 4.21: Growth of Tomato in open sky and in APV

As shown in fig. 4.21, the growth of the Tomato plant in case of open sky farming was around 37 inch whereas in the APV it was 35.1 inch over the period of experimentation. Thus, it can be seen that the average growth of Tomato in case of APV system is slightly lower as compared with the conventional open sky farming.

4.3.3.2 Temperature below PV module

The crops cultivated below the PV modules in the APV system contributes in reduction of the temperature below the PV module. This was evident from the observed data as shown in fig 4.22.

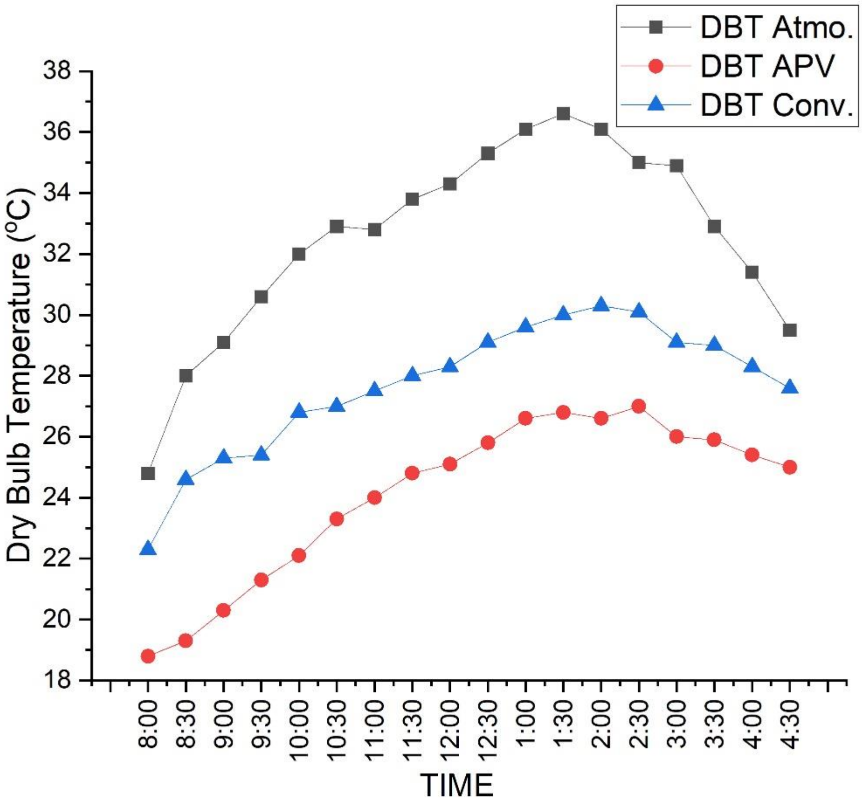


Fig. 4.22: Temperature below PV modules for Tomato Height-1

The average ambient temperature is always higher than the temperature below the PV modules, as shown in fig. 4.22. The temperature below the PV module in an APV system is lower than both the ambient temperature and the temperature below the PV module in conventional PV system, as shown by Fig. 4.22. Further, it has been observed that in an APV system, the temperature below the PV module for Tomato crop with a module height of 1 m was found largely to be 12.54% lower as compared with the conventional PV power plant.

4.3.3.3 Temperature of PV modules

The temperature of the PV modules was recorded in both conventional and APV system, the average values of temperatures for Tomato crop for Height of module as 1 m are shown in fig. 4.23.

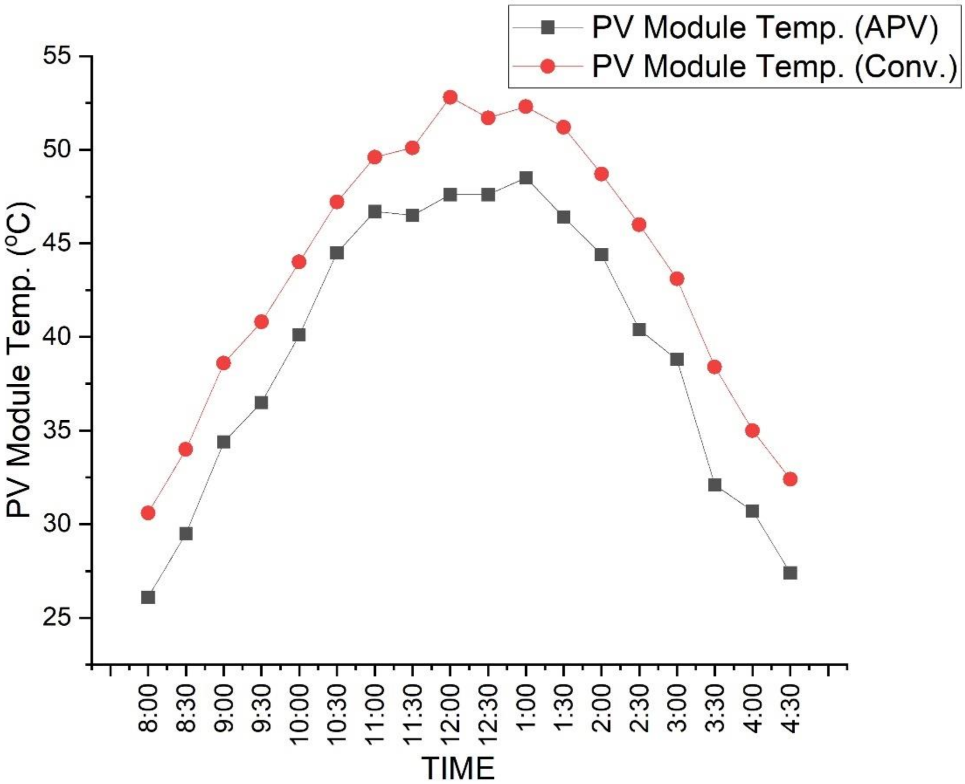


Fig. 4.23: Temperature of PV modules for Tomato Height-1

The temperature of the PV modules in the APV system is always lower than the temperature of the PV modules in the conventional PV power plant, as shown in fig. 4.23. When compared to the PV module temperature in the conventional power plant, the average PV module temperature in APV system for the Tomato crop in Height -I was about 13.06% lower.

4.3.3.4 Power Output of the PV module

The present investigation clearly demonstrated the well-known fact that as the temperature of the crystalline PV module decreases, the power output from the PV module increases. The temperature of the PV module in APV system reduces as compared with the temperature of PV modules in the conventional Power plant. The power output of the APV system in the with the same capacity was higher than the power output of the conventional PV power plant, as illustrated in Fig. 4.24.

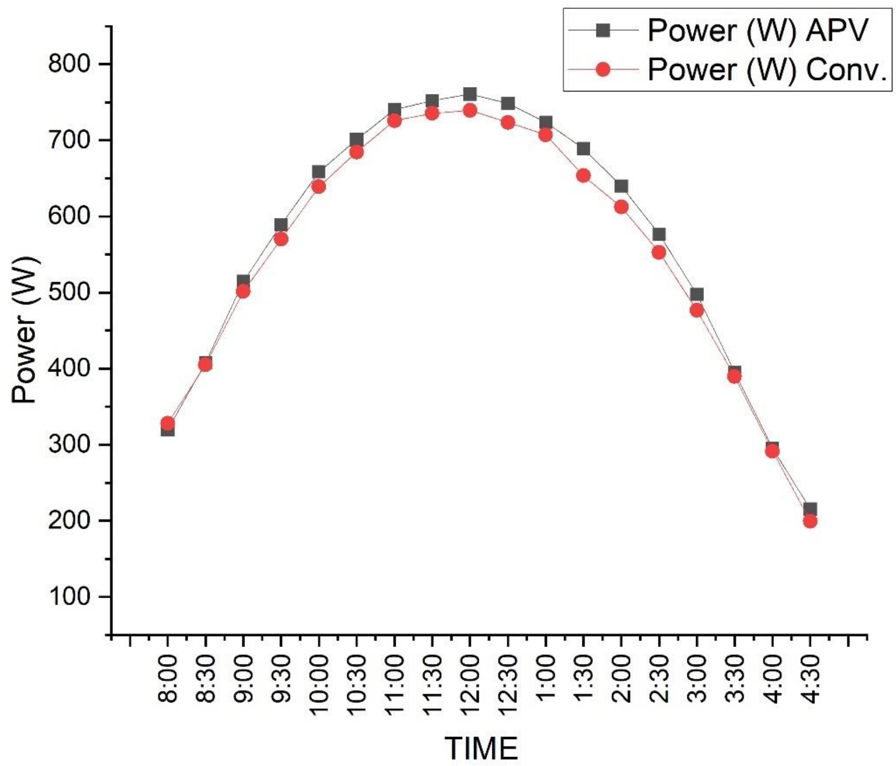


Fig. 4.24: Power output of PV plant for Tomato, Height-1

As seen in fig. 4.24, the power output of an APV system is always greater than the power output of a conventional PV power plant. According to the current experimental investigations, the power output of the APV system was 8.04% higher than the power output of the conventional PV power plant.

4.3.4 Performance investigations of APV system for Tomato for Height-II

The performance of the conventional PV system and the APV system with Tomato crop by maintain the module height as 1.5 m from the ground has been explained in the below text.

4.3.4.1 Growth of Tomato

The growth of the Tomato plant in both open sky farm and below the PV modules in APV system was recorded. Fig. 4.25 shows the comparison between the growth of Tomato crop in open sky and in APV system respectively.

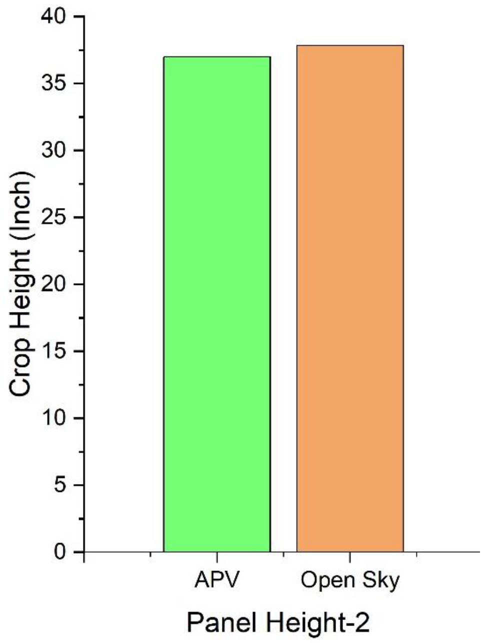


Fig. 4.25: Growth of Tomato in open sky and in APV

As shown in fig. 4.25, the growth of the Tomato plant in case of open sky farming was around 37.8 inch whereas in the APV it was 37 inch over the period of experimentation. Thus, it can be seen that the average growth of Tomato in case of APV system is slightly lower as compared with the conventional open sky farming.

4.3.4.2 Temperature below PV module

The crops cultivated below the PV modules in the APV system contributes in reduction of the temperature below the PV module. This was evident from the observed data as shown in fig 4.26.

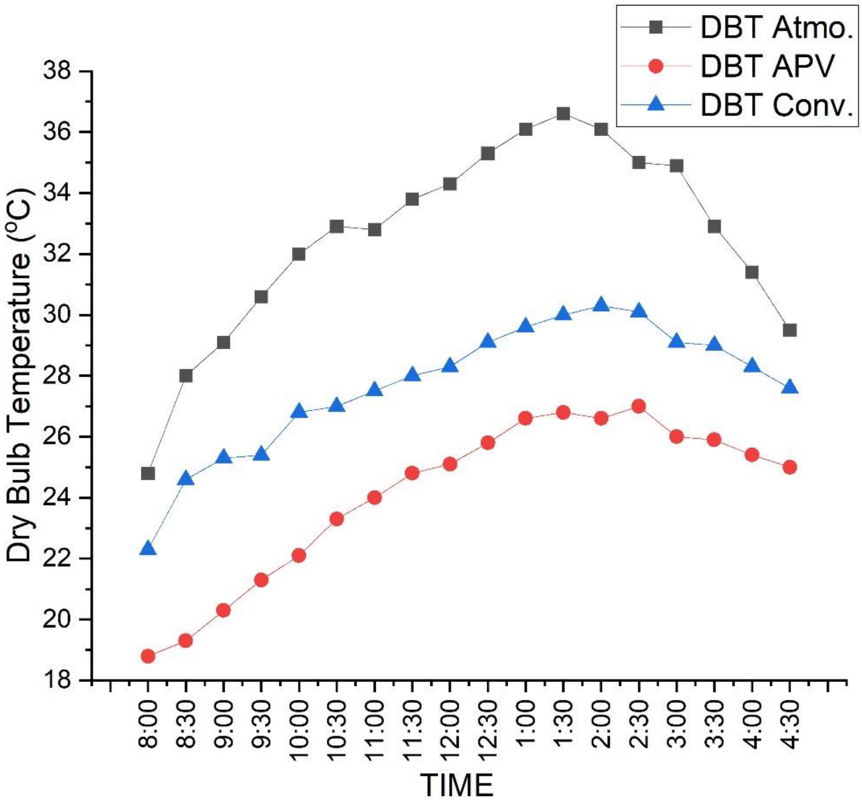


Fig. 4.26: Temperature below PV modules for Tomato Height-II

The average ambient temperature is always higher than the temperature below the PV modules, as shown in fig. 4.26. The temperature below the PV module in an APV system is lower than both the ambient temperature and the temperature below the PV module in conventional PV system, as shown by Fig. 4.26. Further, it has been observed that in an APV system, the temperature below the PV module for Tomato crop with a module height of 1 m was found largely to be 9.76% lower as compared with the conventional PV power plant.

4.3.4.3 Temperature of PV modules

The temperature of the PV modules was recorded in both conventional and APV system, the average values of temperatures for Tomato crop for Height of module as 1 m are shown in fig. 4.27.

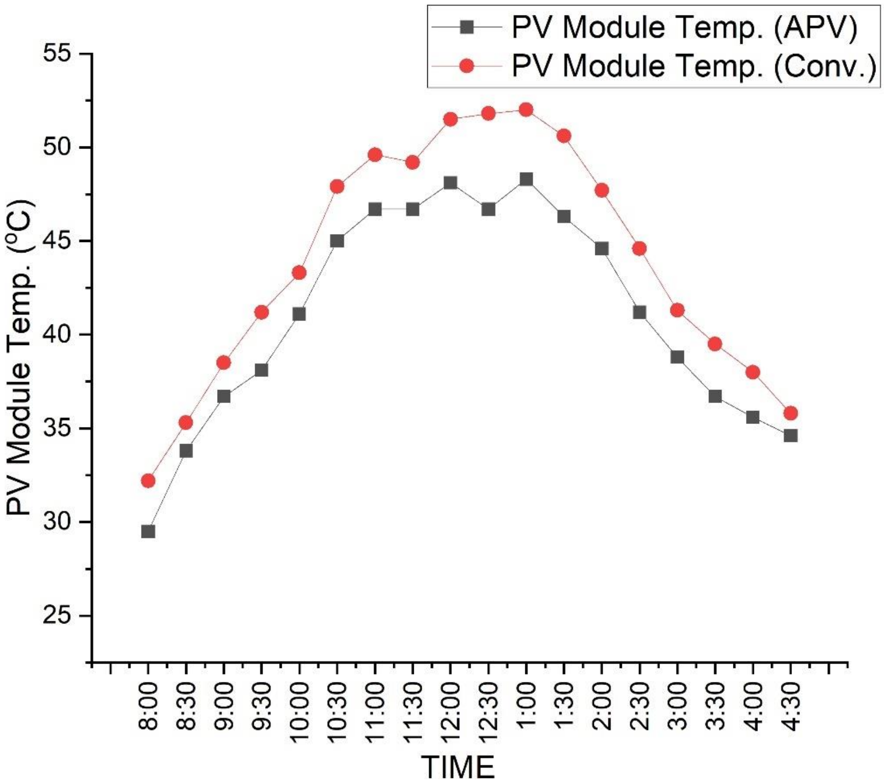


Fig. 4.27: Temperature of PV modules for Tomato Height-II

The temperature of the PV modules in the APV system is always lower than the temperature of the PV modules in the conventional PV power plant, as shown in fig. 4.27. When compared to the PV module temperature in the conventional power plant, the average PV module temperature in APV system for the Tomato crop in Height -I was about 12.38% lower.

4.3.4.4 Power Output of the PV module

The present investigation clearly demonstrated the well-known fact that as the temperature of the crystalline PV module decreases, the power output from the PV module increases. The temperature of the PV module in APV system reduces as compared with the temperature of PV modules in the conventional Power plant. The power output of the APV system in the with the same capacity was higher than the power output of the conventional PV power plant, as illustrated in Fig. 4.28.

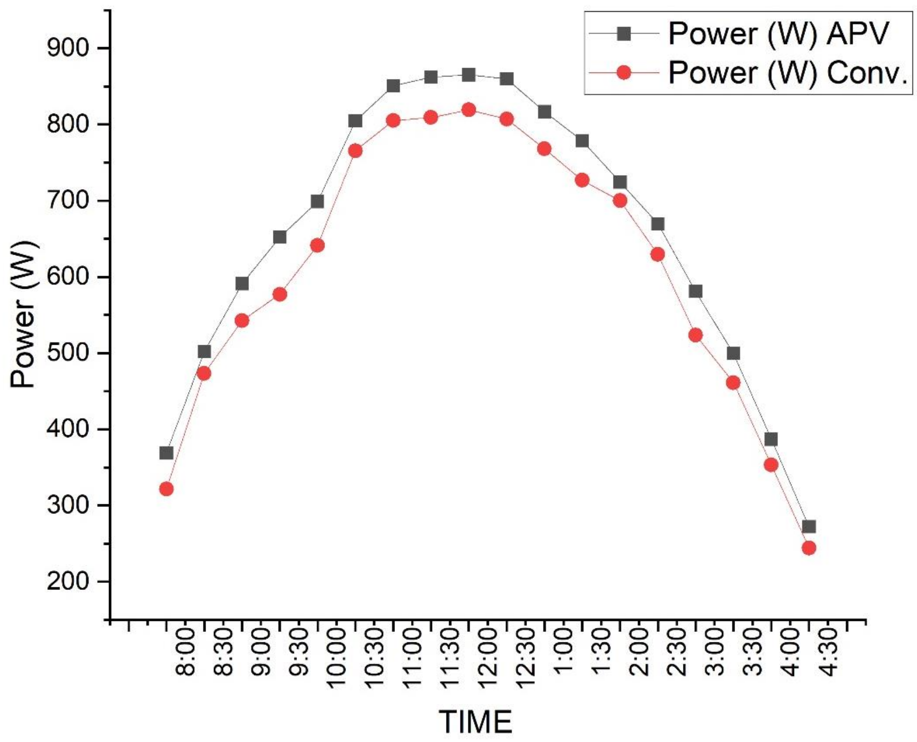


Fig. 4.28: Power output of PV plant for Tomato, Height-II

As seen in fig. 4.28, the power output of an APV system is always greater than the power output of a conventional PV power plant. According to the current experimental investigations, the power output of the APV system was 6.75% higher than the power output of the conventional PV power plant.

4.3.5 Performance investigations of APV system for Spinach for Height-I

The performance of the conventional PV system and the APV system with Spinach crop by maintain the module height as 1 m from the ground has been explained in the below text.

4.3.5.1 Growth of Spinach

The growth of the Spinach plant in both open sky farm and below the PV modules in APV system was recorded. Fig. 4.29 shows the comparison between the growth of Spinach crop in open sky and in APV system respectively.

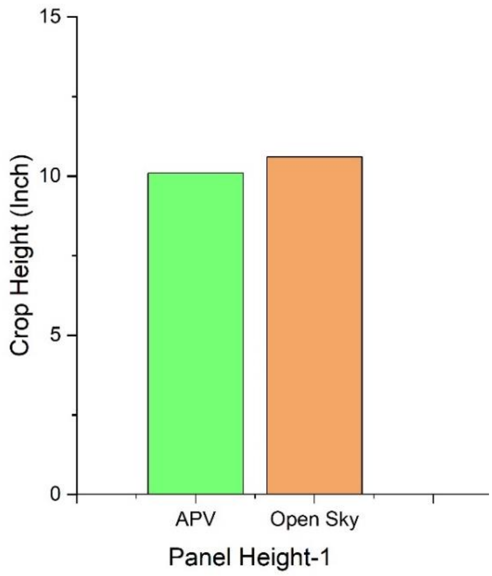


Fig. 4.29: Growth of Spinach in open sky and in APV

As shown in fig. 4.29, the growth of the Spinach plant in case of open sky farming was around 10.6 inch whereas in the APV it was 10.1 inch over the period of experimentation. Thus, it can be seen that the average growth of Spinach in case of APV system is slightly lower as compared with the conventional open sky farming.

4.3.5.2 Temperature below PV module

The crops cultivated below the PV modules in the APV system contributes in reduction of the temperature below the PV module. This was evident from the observed data as shown in fig 4.30.

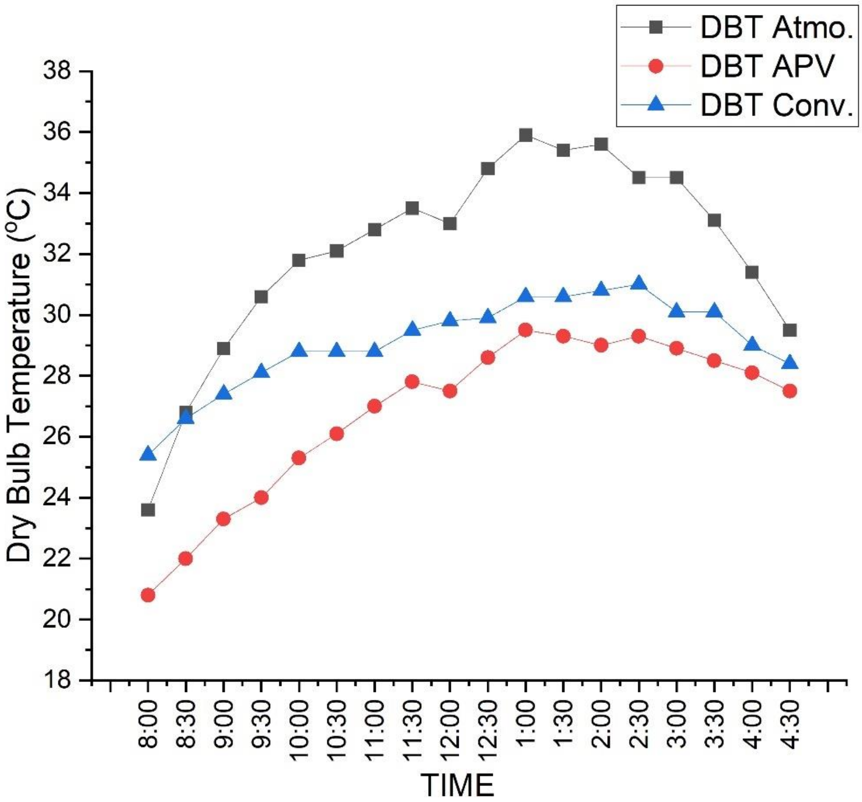


Fig. 4.30: Temperature below PV modules for Spinach Height-I

The average ambient temperature is always higher than the temperature below the PV modules, as shown in fig. 4.30. The temperature below the PV module in an APV system is lower than both the ambient temperature and the temperature below the PV module in conventional PV system, as shown by Fig. 4.30. Further, it has been observed that in an APV system, the temperature below the PV module for Spinach crop with a module height of 1 m was found largely to be 11.57% lower as compared with the conventional PV power plant.

4.3.5.3 Temperature of PV modules

The temperature of the PV modules was recorded in both conventional and APV system, the average values of temperatures for Spinach crop for Height of module as 1 m are shown in fig. 4.31.

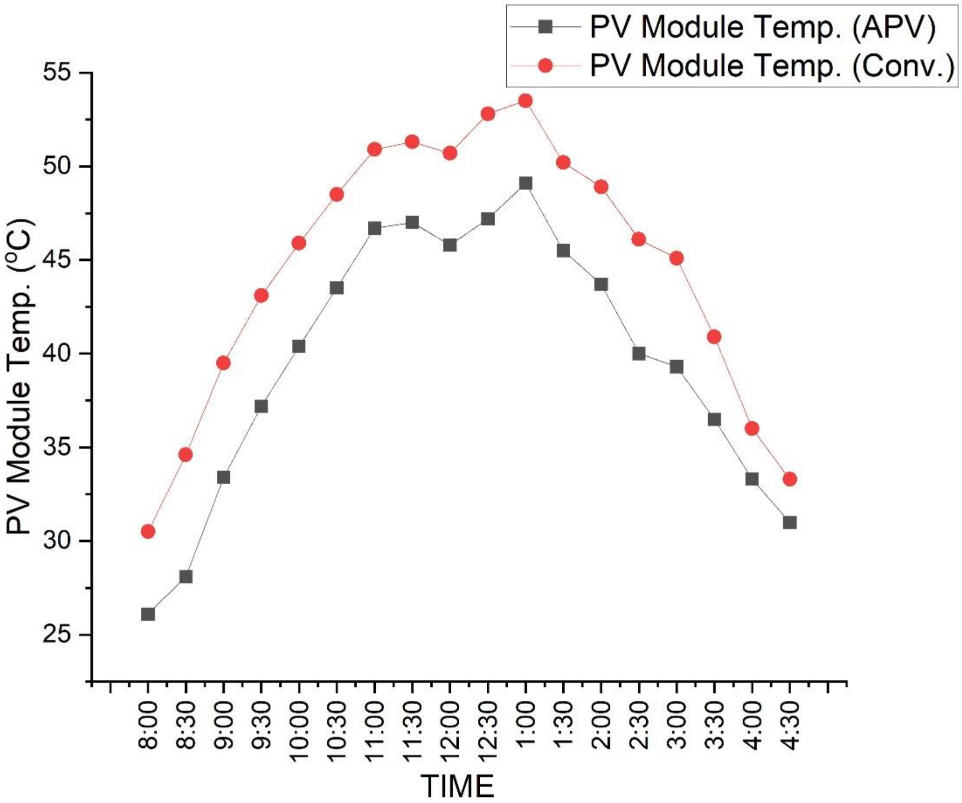


Fig. 4.31: Temperature of PV modules for Spinach Height-I

The temperature of the PV modules in the APV system is always lower than the temperature of the PV modules in the conventional PV power plant, as shown in fig. 4.31. When compared to the PV module temperature in the conventional power plant, the average PV module temperature in APV system for the Spinach crop in Height -I was about 12.31% lower.

4.3.5.4 Power Output of the PV module

The present investigation clearly demonstrated the well-known fact that as the temperature of the crystalline PV module decreases, the power output from the PV module increases. The temperature of the PV module in APV system reduces as compared with the temperature of PV modules in the conventional Power plant. The power output of the APV system in the with the same capacity was higher than the power output of the conventional PV power plant, as illustrated in Fig. 4.32.

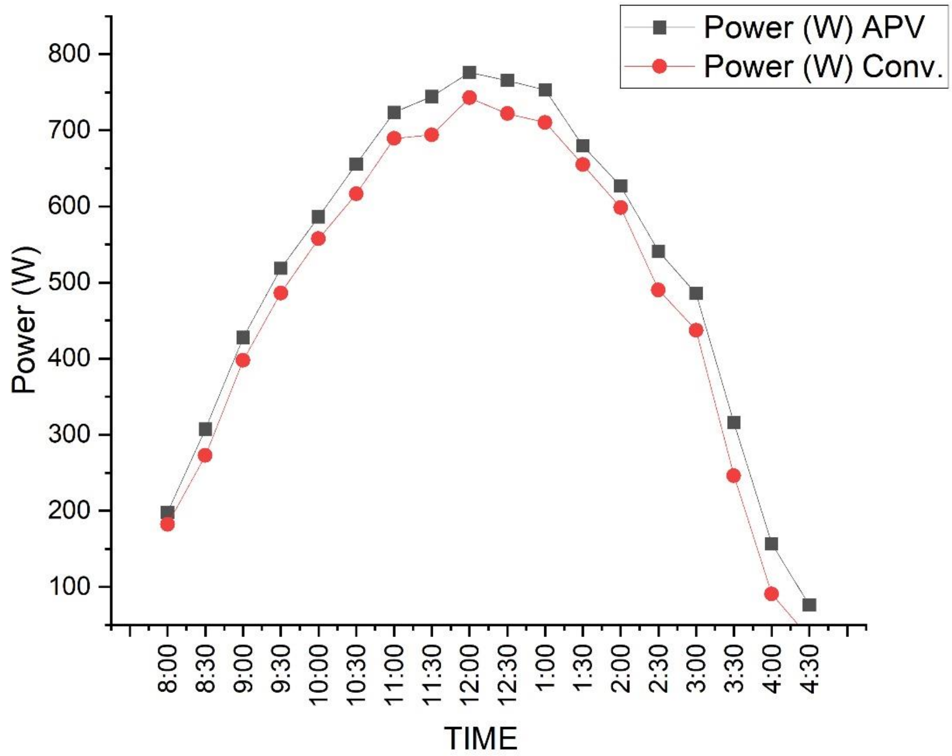


Fig. 4.32: Power output of PV plant for Spinach, Height-I

As seen in fig. 4.32, the power output of an APV system is always greater than the power output of a conventional PV power plant. According to the current experimental investigations, the power output of the APV system was 7.43% higher than the power output of the conventional PV power plant.

4.3.6 Performance investigations of APV system for Spinach for Height-II

The performance of the conventional PV system and the APV system with Spinach crop by maintain the module height as 1.5 m from the ground has been explained in the below text.

4.3.6.1 Growth of Spinach

The growth of the Spinach plant in both open sky farm and below the PV modules in APV system was recorded. Fig. 4.33 shows the comparison between the growth of Spinach crop in open sky and in APV system respectively.

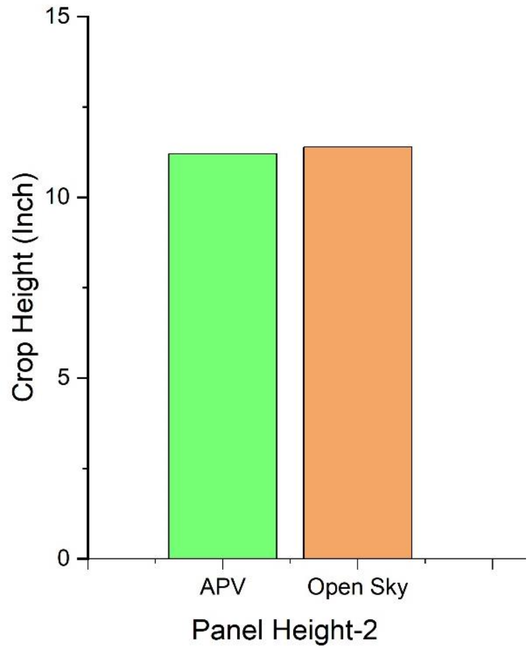


Fig. 4.33: Growth of Spinach in open sky and in APV

As shown in fig. 4.33, the growth of the Spinach plant in case of open sky farming was around 11.2 inch whereas in the APV it was 11.4 inch over the period of experimentation. Thus, it can be seen that the average growth of Spinach in case of APV system is slightly lower as compared with the conventional open sky farming.

4.3.6.2 Temperature below PV module

The crops cultivated below the PV modules in the APV system contributes in reduction of the temperature below the PV module. This was evident from the observed data as shown in fig 4.34.

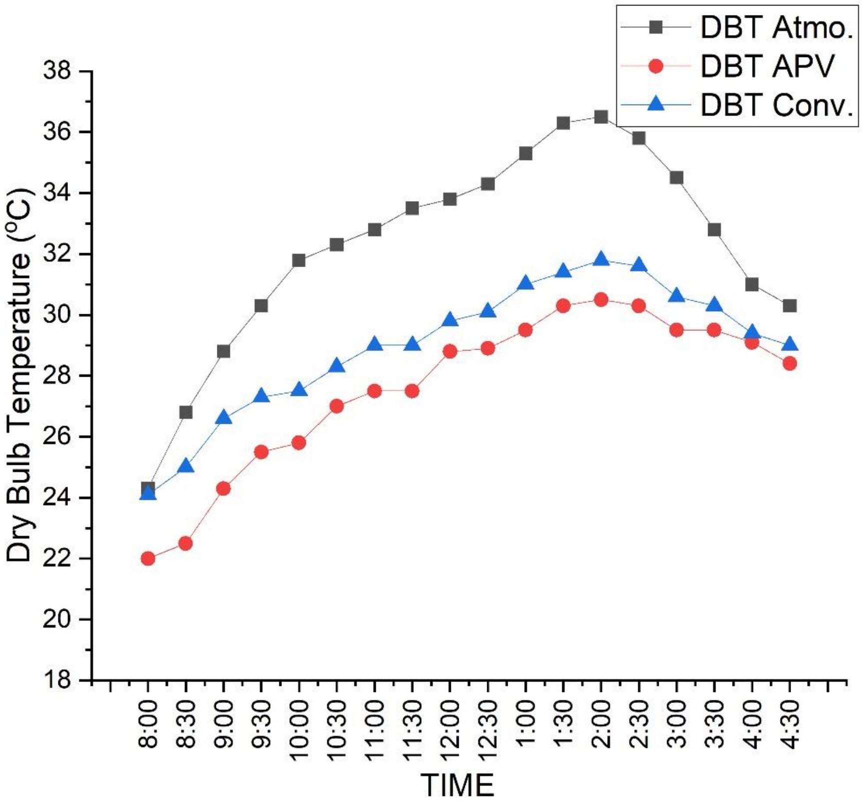


Fig. 4.34: Temperature below PV modules for Spinach Height-II

The average ambient temperature is always higher than the temperature below the PV modules, as shown in fig. 4.34. The temperature below the PV module in an APV system is lower than both the ambient temperature and the temperature below the PV module in conventional PV system, as shown by Fig. 4.34. Further, it has been observed that in an APV system, the temperature below the PV module for Spinach crop with a module height of 1.5 m was found largely to be 10.14% lower as compared with the conventional PV power plant.

4.3.6.3 Temperature of PV modules

The temperature of the PV modules was recorded in both conventional and APV system, the average values of temperatures for Spinach crop for Height of module as 1.5 m are shown in fig. 4.35.

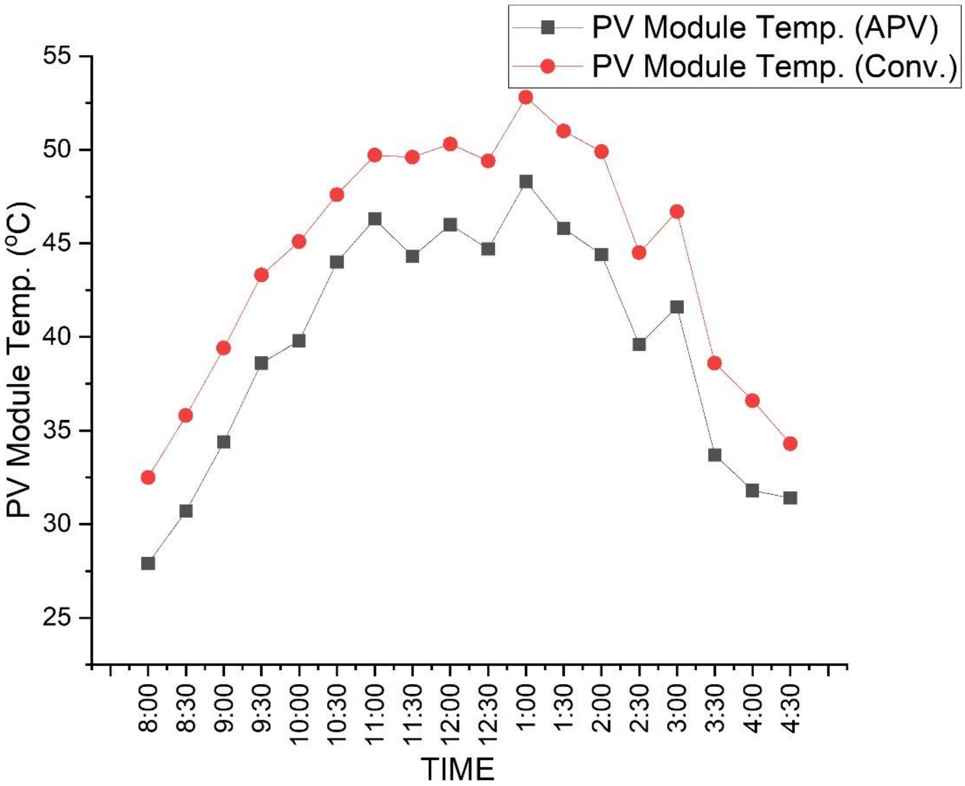


Fig. 4.35: Temperature of PV modules for Spinach Height-II

The temperature of the PV modules in the APV system is always lower than the temperature of the PV modules in the conventional PV power plant, as shown in fig. 4.35. When compared to the PV module temperature in the conventional power plant, the average PV module temperature in APV system for the Spinach crop in Height -I was about 11.77% lower.

4.3.6.4 Power Output of the PV module

The present investigation clearly demonstrated the well-known fact that as the temperature of the crystalline PV module decreases, the power output from the PV module increases. The temperature of the PV module in APV system reduces as compared with the temperature of PV modules in the conventional Power plant. The power output of the APV system in the with the same capacity was higher than the power output of the conventional PV power plant, as illustrated in Fig. 4.36.

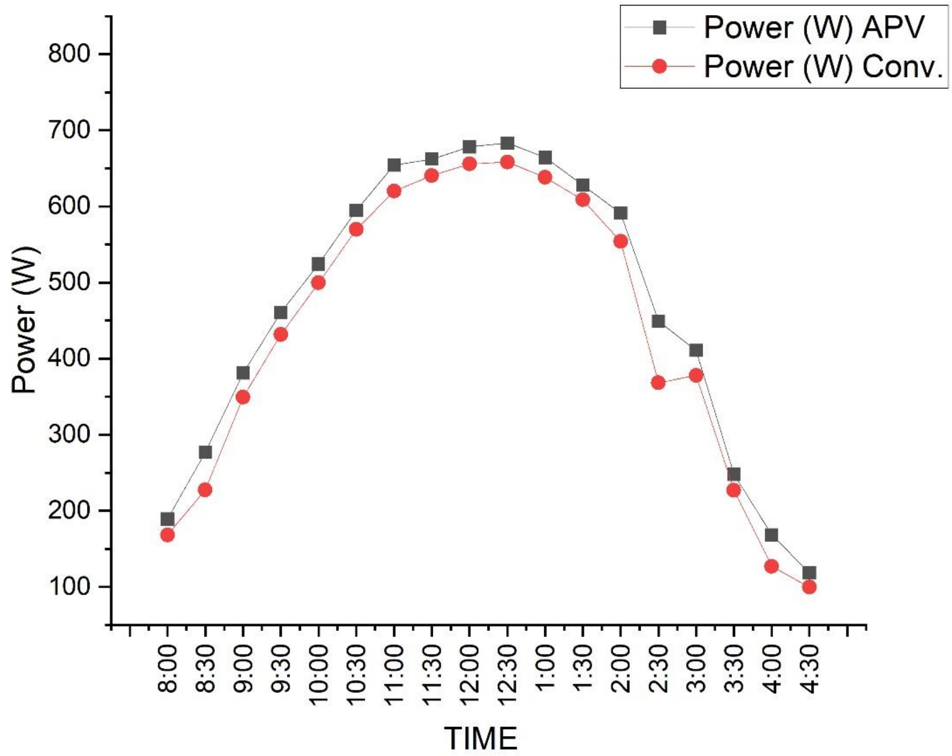


Fig. 4.36: Power output of PV plant for Spinach, Height-II

As seen in fig. 4.36, the power output of an APV system is always greater than the power output of a conventional PV power plant. According to the current experimental investigations, the power output of the APV system was 6.55% higher than the power output of the conventional PV power plant.

Chapter-5

Analysis of APV systems

Based on experimental studies, this chapter describes the performance analysis of APV systems. The study focuses on the effect of crop cultivation on PV plant efficiency, PV daily electricity generation, and the Land Equivalent Ratio (LER). Furthermore, the potential benefits of an APV system for a Megawatt capacity power plant due to improved electrical yield have been discussed.

5.1 Daily Electricity generation by APV system

As discussed in Chapter 4, the temperature of the PV module in the APV system is lower than the temperature of the module in the conventional power plant. As the operating temperature of the solar PV module decreases, the electrical output of the solar PV system increases. As a result, the power output of the APV system was greater than the power output of the conventional PV plant.

The power output of the solar PV modules at a given irradiance and the sunshine hours determine the daily electricity generation by the solar PV system. The conventional PV plant and the APV plant with different crops were installed side by side in the present experiment. Both power plants were built at the same inclination and did receive the exact same amount of irradiance for the same sunshine hours. The module make and model (quality of PV module), mounting structure inclination, orientation, cleaning frequency, length of connector cables, and load (both strings are connected to the same grid) are identical in both conventional and APV systems. Despite these similarities, the electrical output of the APV system is greater than that of the conventional PV plant.

The following paragraphs shows the average daily power generations by the APV system developed in the present study.

5.1.1 Daily Electricity generation by APV system for Aloe Vera crop

Fig. 5.1 (a), and Fig. 5.1 (b) shows the daily electricity generation by the conventional and APV system with Aloe Vera crops for height -1 and height -2 respectively.

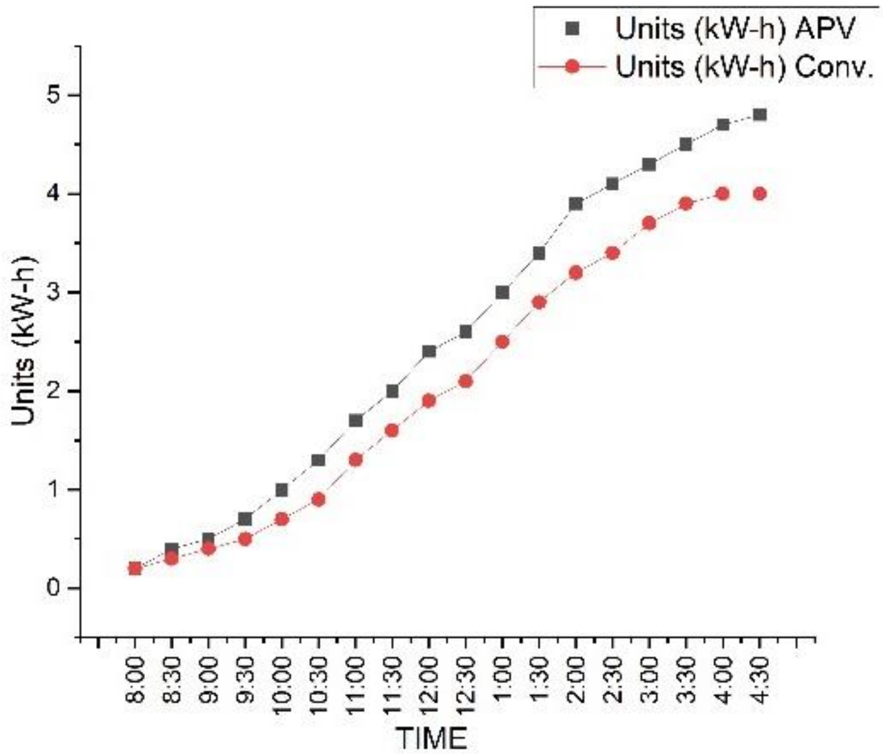


Fig. 5.1 (a) Daily electricity generation by conventional and APV system for Aloe Vera Height -1

As shown in fig. 5.1 (a), the average daily electricity generation by the APV plant is continuously higher as compared with the conventional PV plant. On an average the daily electricity generation by the APV plant for Aloe Vera Height -1 is 13.69% higher as compared with the conventional power plant.

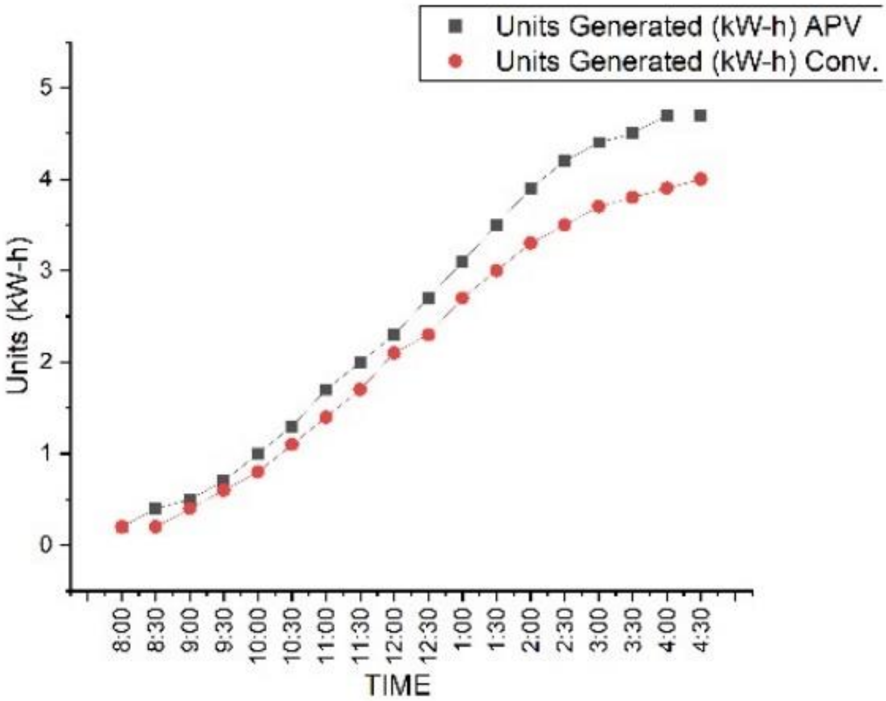


Fig. 5.1 (b) Daily electricity generation by conventional and APV system for Aloe Vera Height -2

As shown in fig. 5.1 (b) the average daily electricity generation by the APV plant is continuously higher as compared with the conventional PV plant. On an average the daily electricity generation by the APV plant for Aloe Vera Height -2 is 14.13% higher as compared with the conventional power plant.

5.1.2 Daily Electricity generation by APV system for Tomato crop

Fig. 5.2 (a), and Fig. 5.2 (b) shows the daily electricity generation by the conventional and APV system with Tomato crops for height -1 and height -2 respectively.

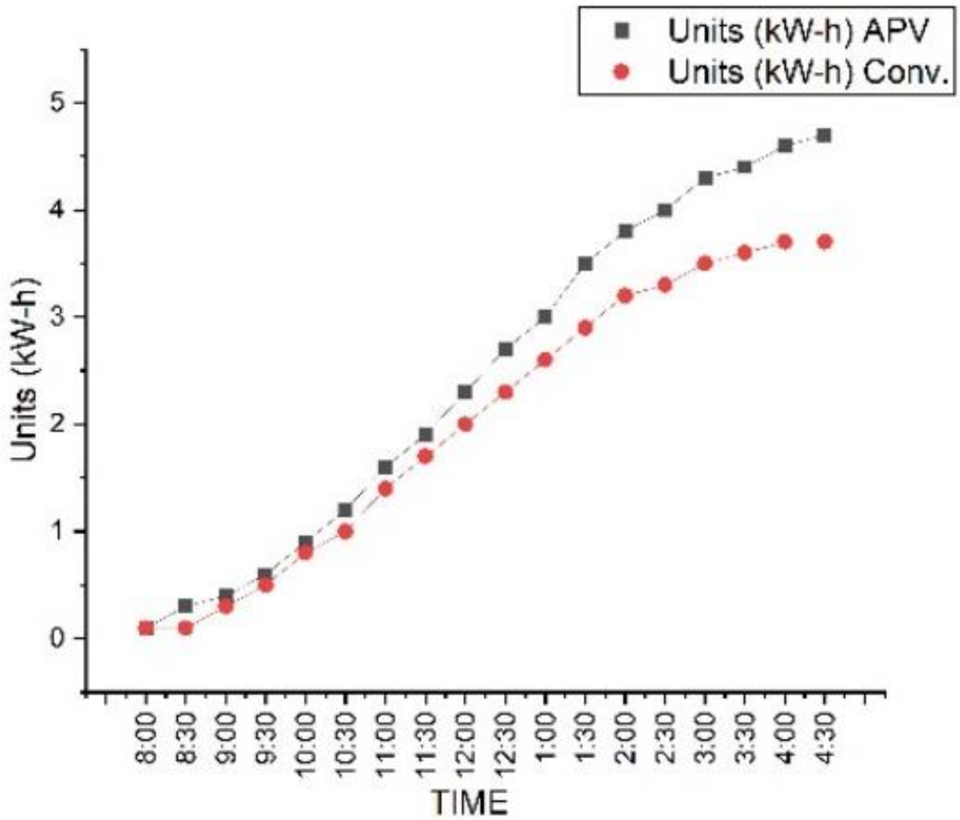


Fig. 5.2 (a) Daily electricity generation by conventional and APV system for Tomato Height -1

As shown in fig. 5.1 (a), the average daily electricity generation by the APV plant is continuously higher as compared with the conventional PV plant. On an average the daily electricity generation by the APV plant for Tomato Height -1 is 14.53% higher as compared with the conventional power plant.

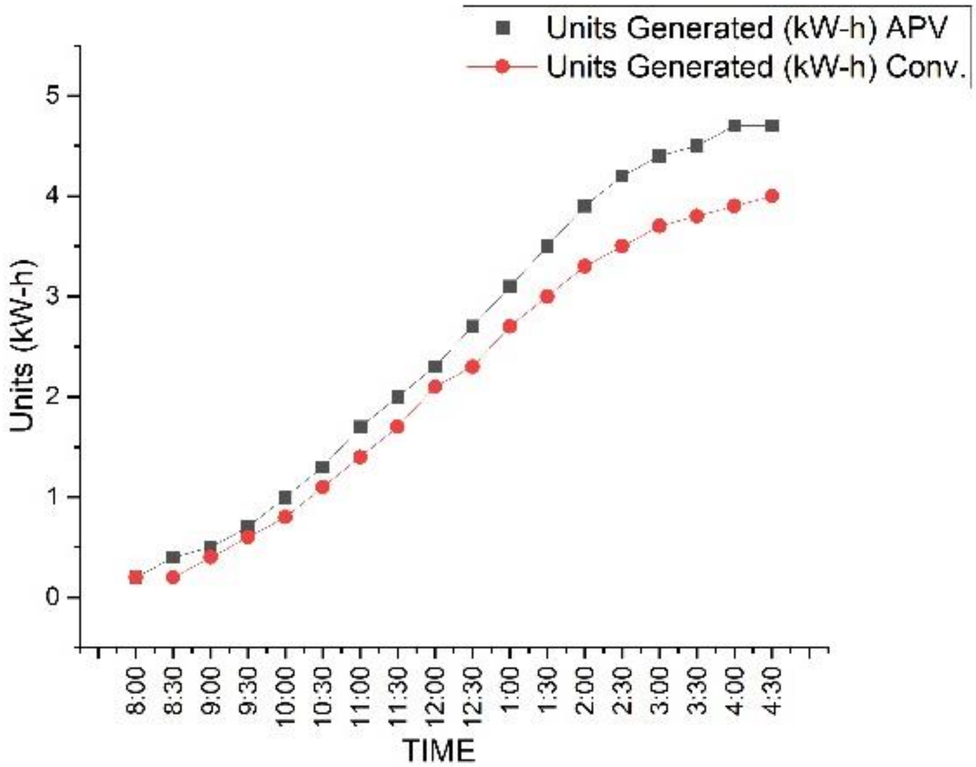


Fig. 5.2 (b) Daily electricity generation by conventional and APV system for Tomato Height -2

As shown in fig. 5.1 (b) the average daily electricity generation by the APV plant is continuously higher as compared with the conventional PV plant. On an average the daily electricity generation by the APV plant for Tomato Height -2 is 13.64% higher as compared with the conventional power plant.

5.1.3 Daily Electricity generation by APV system for Spinach crop

Fig. 5.3 (a), and Fig. 5.3 (b) shows the daily electricity generation by the conventional and APV system with Spinach crops for height -1 and height -2 respectively.

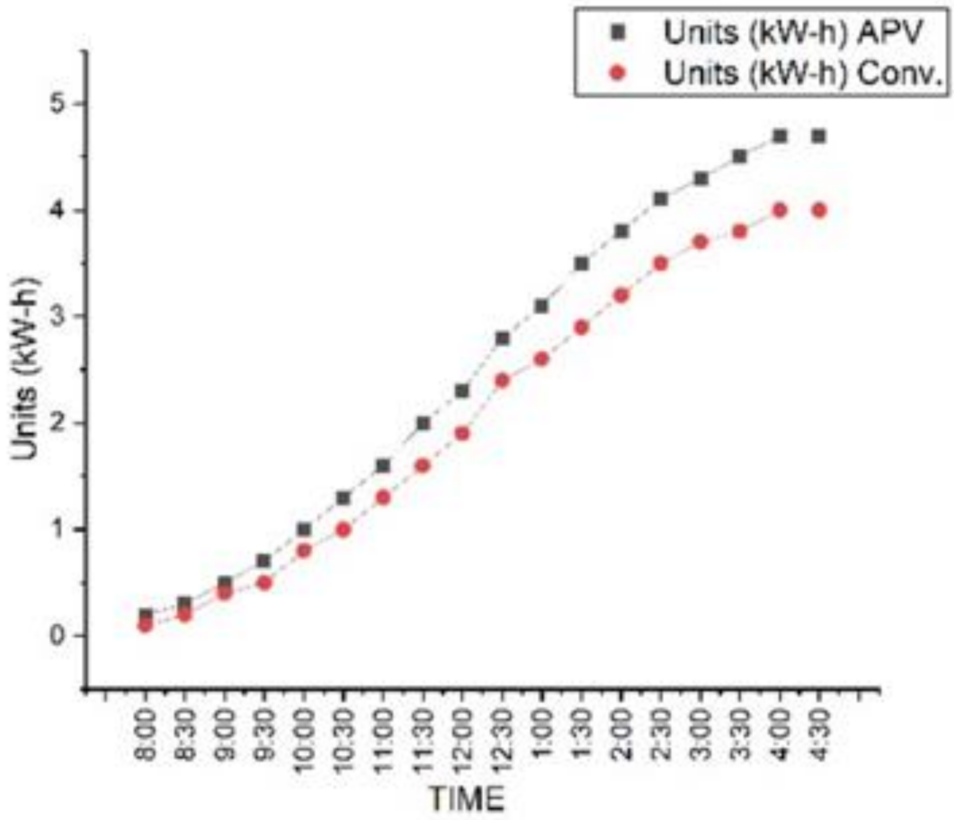


Fig. 5.3 (a) Daily electricity generation by conventional and APV system for Spinach Height -1

As shown in fig. 5.3 (a), the average daily electricity generation by the APV plant is continuously higher as compared with the conventional PV plant. On an average the daily electricity generation by the APV plant for Spinach Height -1 is 14.92% higher as compared with the conventional power plant.

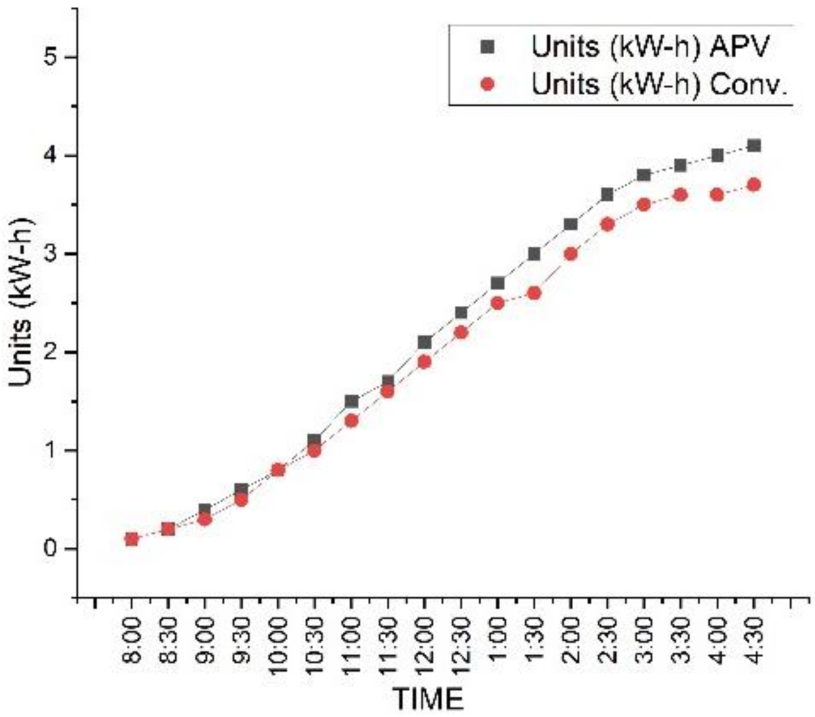


Fig. 5.3 (b) Daily electricity generation by conventional and APV system for Spinach Height -2

As shown in fig. 5.3 (b) the average daily electricity generation by the APV plant is continuously higher as compared with the conventional PV plant. On an average the daily electricity generation by the APV plant for Spinach Height -2 is 10.01% higher as compared with the conventional power plant.

5.2 Electrical Efficiency of the APV system

The electrical efficiency of the solar PV module is calculated using equation 5.1

As below

$$Electrical\ Efficieny\ of\ the\ Solar\ PV\ module = \frac{Output\ of\ the\ Solar\ PV\ module}{Effective\ area\ of\ solar\ PV\ module\ X\ Irradiance} \quad 5.1$$

Equation 5.1 is used to calculate the electrical efficiency of the conventional PV plant and the APV plant. The calculated efficiency is based on the average of actual observations collected during the month of July to March for all the crops and all the module heights. Fig. 5.4 shows the average electrical efficiency of the conventional and APV plant.

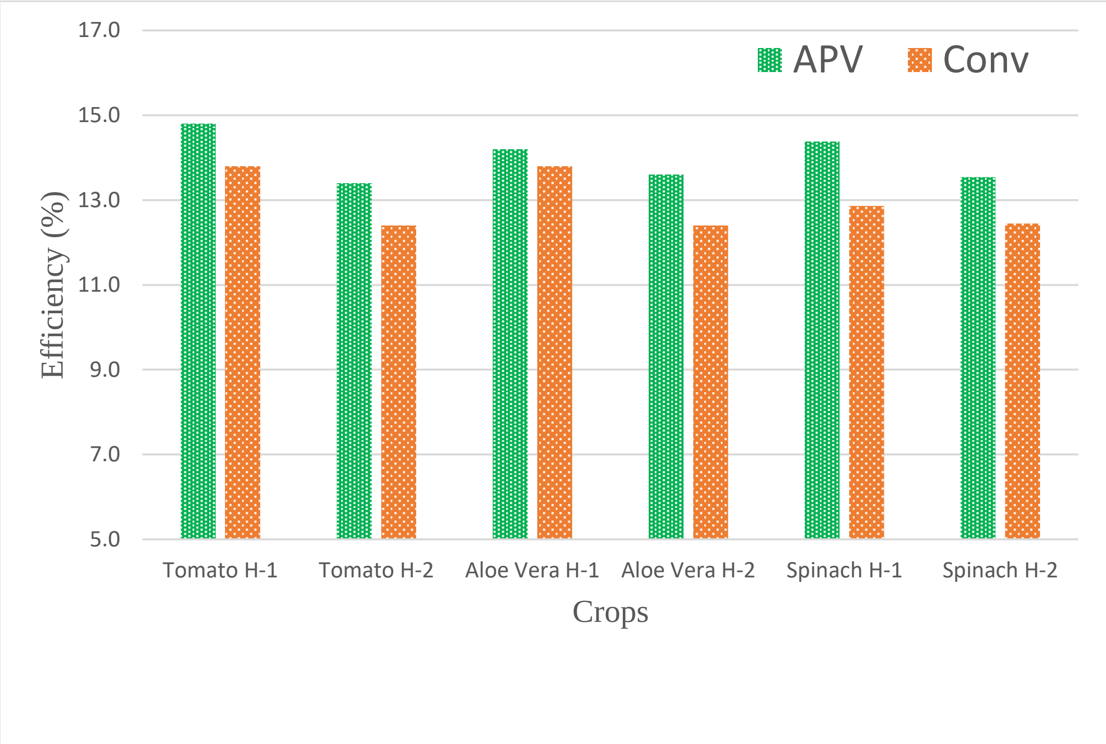


Fig. 5.4: Electrical efficiency of the conventional and APV plant

As shown in fig. 5.4, the electrical efficiency of the APV plant is always higher as compared with the conventional PV plant. The calculations shows that the highest efficiency of the APV power plant was obtained for Tomato height-I crop.

5.3 Land Equivalent Ratio (LER)

Land Equivalent Ratio (LER) is used to quantify the land use efficiency. LER is defined as the ratio of total yield by dual production (Electricity + Crop yield) to the crop yield alone. It is calculated using equation 5.2 as below

$$LER = \frac{Yield\ \ of\ APV\ system\ (Crop\ 1 + Electricity)}{Yield\ (Crop\ 1)} + \frac{Yield\ \ of\ APV\ system\ (Crop\ n + Electricity)}{Yield\ (Crop\ n)} \qquad 5.2$$

LER <1 indicates that the APV system is less productive than separate production. On the other hand, LER >1 indicates increased productivity in the APV system as compared to the crop production alone. [62] have studied the productivity of APV system for different crops such as Potato, Winter wheat, Celeriac, clover grass and identified different LERs in the range of 1.5 to 1.8.

The Land Equivalent Ratio (LER) has been calculated based on the experimental observations of the present study. Table 5.1 shows the calculated Land Equivalent Ratio (LER) for the APV systems developed in the present study.

Table 5.1: Land Equivalent Ratio

	Panel Height		Crop Height (Inch)	Gen Units	LER=((Ycrop APV)/(Ycrop Conv)) +((YkWh APV)/YkWh conv))
Tomato	Tomato Panel Height-1	APV	35.1	4.7	2.219
		Open Sky	37.0	3.7	
	Tomato Panel Height-2	APV	37.0	4.7	2.153
		Open Sky	37.8	4.0	
Spinach	Spinach Panel Height-1	APV	10.1	4.7	2.126
		Open Sky	10.6	4	
	Spinach Panel Height-2	APV	11.2	4.1	2.085
		Open Sky	11.4	3.7	
Aloe Vera	Aloe Vera Panel Height-1	APV	11.40	4.8	2.088
		Open Sky	12.83	4	
	Aloe Vera Panel Height-2	APV	11.96	4.7	2.084
		Open Sky	13.60	3.9	

Fig. 5. 5 shows the LER for all the crops used in the present work

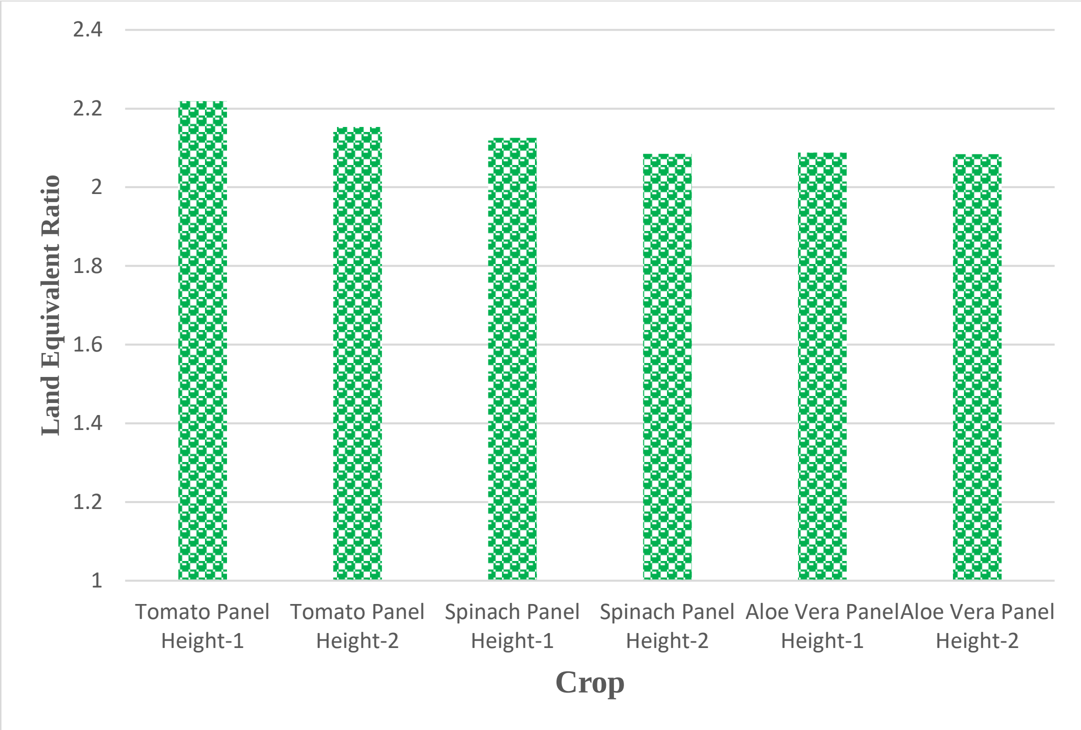


Fig. 5.5: Land Equivalent Ratio

As shown in fig. 5.5, the LER values for all the crops are greater than 1, it clearly indicates the increased productivity in the APV system as compared to the crop production alone. Moreover, the highest the highest LER was obtained for Tomato crop in Height -1.

5.4 Estimation of energy yield by 1 MW APV plant

Based on the experimental studies, the observations, and the subsequent calculations it has been observed that the electrical efficiency and in turn power output of the solar PV plant is improved by converting it to APV system. In the present study the observations show that on an average the APV system generates 0.4 to 0.6 kWh/ kw/day units of additional energy as compared with the conventional solar PV plant. Based on this, the calculations for a 1 MW APV plant have been carried out for all the crops as shown in fig 5.6.

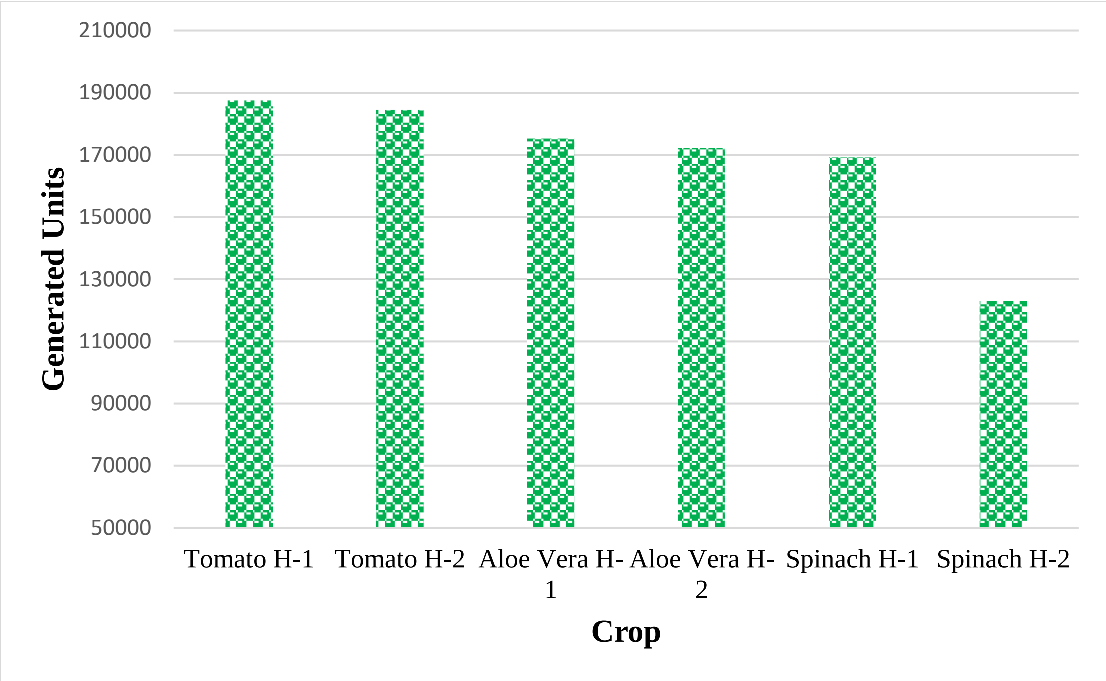


Fig. 5.6: Additional Electricity generated by 1MW APV plant

The APV system with tomato crop for module height of 1 m from ground can generate 187500 kWh additional units of electricity per year, as shown in fig. 5.5. The results are similar for the other crops as well. In addition, the yield of the tomato crop and other crops is comparable to that of open sky farming. This demonstrates the utility of an APV plant not only for dual land use, but also for improved electrical yield.

Chapter-6

Performance prediction of APV system using Analytical Techniques

This chapter aimed at development of an analytical framework to predict the performance of the APV plant at any given location. The theoretical frame work gives a predictive model for power estimation of the APV plant based on the reduction in PV module temperature in APV system. The predictive model considers the outcomes of the regression analysis of module temperature that was developed based on the experimental findings.

6.1 Methodology for the theoretical performance prediction

To predict the performance of APV system for any given location and for any given crops a systematic analytical procedure has been formulated. The procedure is shown in fig.6.1. According to procedure, at first the irradiations and the optimum tilt angle for the module installations is to be estimated. For the estimation of power output, parameters like the plant capacity, crops, crop height, module spacing, etc are required to consider. Based on the findings of the present research work, a regression model has been developed which can estimate the PV module temperature and then the corresponding power output from the system.

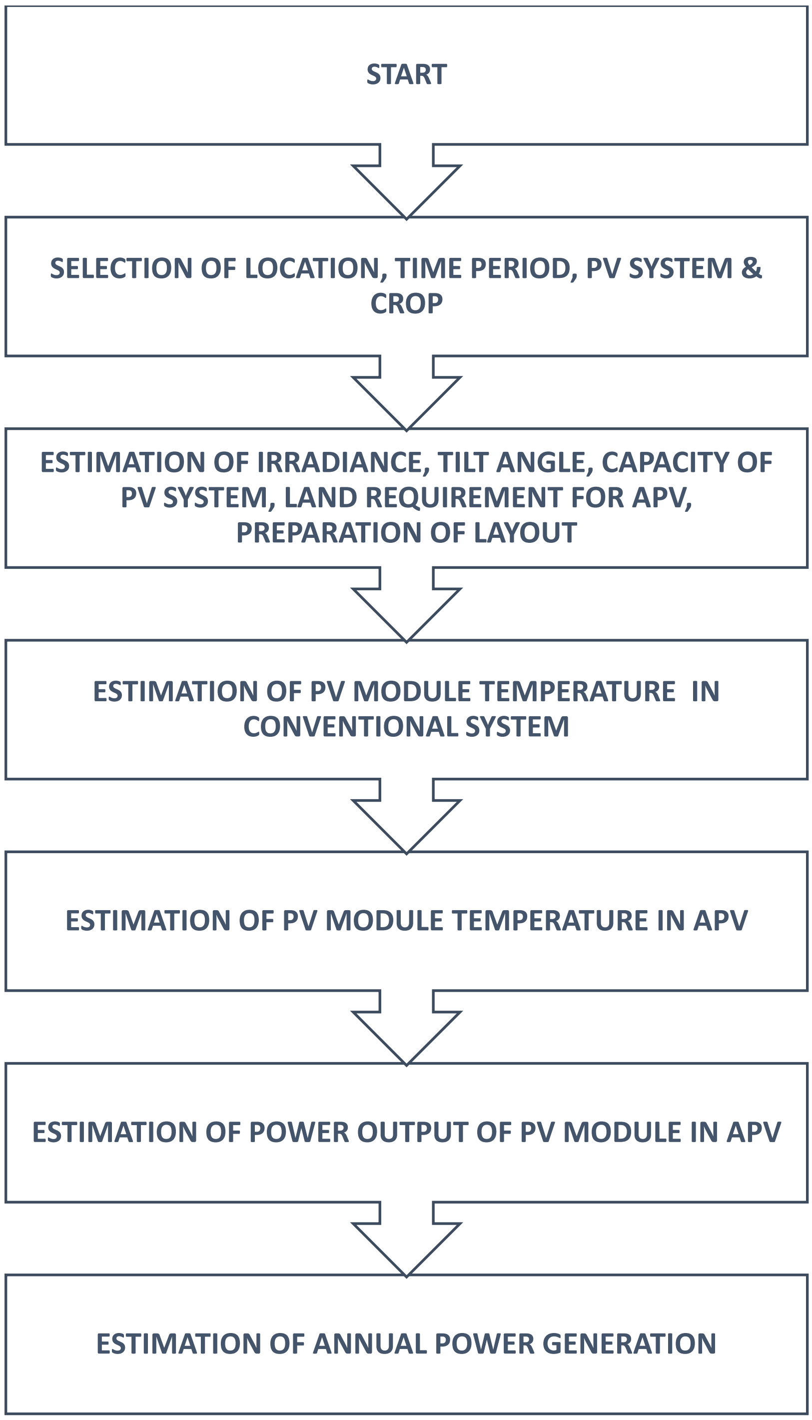


Figure 6.1: Theoretical Estimation of Performance of APV Plant

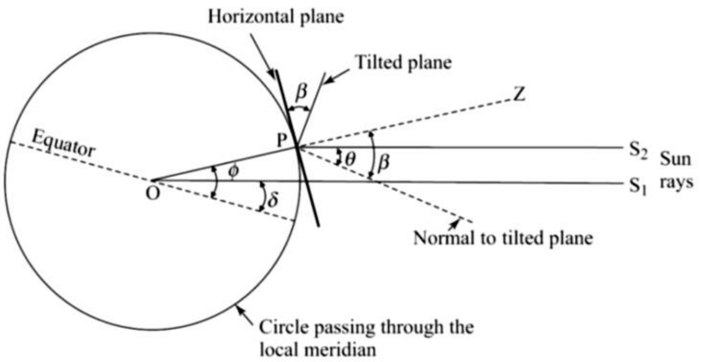
The detailed steps as shown in fig.6.1 are discussed in the subsequent text.

6.2 Estimation of incoming irradiations

Gopinathan model was used to estimate the components of global radiations [11]. The estimation procedure given by Kacira M et al [34] was used for the tilt angle calculations. The procedure suggested by Gueymard [36] and S. P. Sukhatme [2] was used for the estimation of incidence angle and radiations.

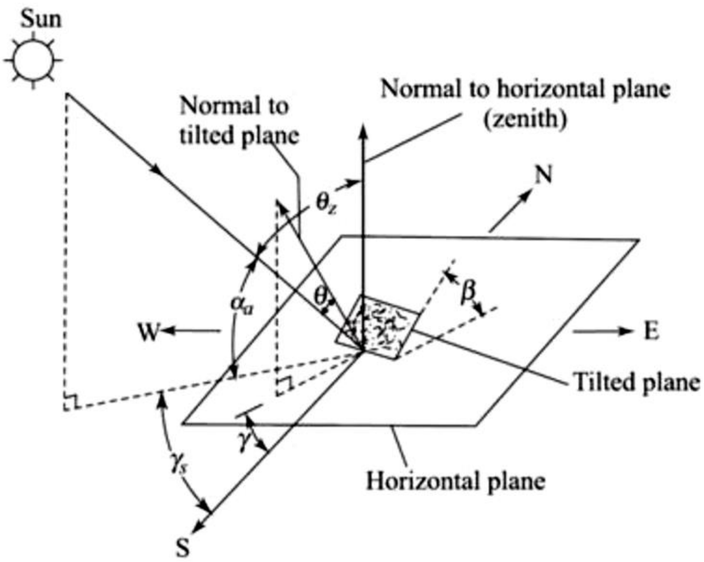
6.2.1 Estimation of radiations available at location

The various useful angles of the earth sun geometry are shown in fig. 6.2 (a)and in fig. 6.2(b)



(ϕ – Latitude angle, δ- Declination angle, β- tilt angle)

Fig. 6.2 (a): Latitude and declination angle [2]



(θ- Angle of incidence, θ_z- zenith angle, α_a – solar altitude angle, γ- Azimuth angle)

Fig. 6.2 (b): Different angles in the solar geometry [2] equation. (6.1) [2] was used to calculate the declination angle

$$\delta = 23.45 \times \sin [(360/365) \times (284 + n)] \quad 6.1$$

Equation (6.2) [2] was used to calculate the angle of incidence

$$\cos(\theta) = \sin(\delta) \times \sin(\phi-\beta) + \cos(\delta)\cos(\omega) \cos (\phi-\beta) \quad 6.2$$

Equations (6.3 –6.10) were used to calculate the components of radiations

$$\frac{Ig}{Hg} = \frac{Io}{Ho} [a + \frac{bcos(\omega)}{Fc}] \quad 6.3$$

$$Fc = a + 0.5b[\frac{\left(\frac{\pi\omega s}{180}\right) - (\sin \omega s\ x\ coc\ \omega s)}{(sin\omega s - \left(\frac{\pi\omega s}{180}\right) x \cos \omega s}] \quad 6.4$$

$$a = 0.409 + 0.5016 \sin (\omega s - 60) \quad 6.5$$

$$b = 0.6609 - 0.4767 \sin (\omega s - 60) \quad 6.6$$

Monthly average daily global radiations [35]

$$\frac{Hg}{Ho} = (a + b) \frac{Dl}{Dl\ max} \quad 6.7$$

$$Ho = \frac{24}{\pi} Isc [1.033 \cos (360n/365)] (\omega s \sin(\phi) \sin(\delta) + \cos(\phi) \cos(\delta) \sin(\omega s)) \quad 6.8$$

The monthly average daily diffused radiations [36]

$$\frac{Hd}{Hg} = 0.8677 - 0.7365 [\frac{Dl}{Dl\ max}] \quad 6.9$$

Monthly average hourly diffused radiations [37]

$$\frac{Id}{Hd} = \frac{Io}{Ho} \quad 6.10$$

6.2.2 Calculations for tilt angle for APV installation

Equation (6.11) was used to calculate the tilt angle for the installation.

$$\beta(opt) = \tan^{-1} [\frac{\{\sum_{k=1}^{12} (H(b) \tan(\phi - \delta)\}}{\sum_1^{12} H(b)}] \quad 6.11$$

For Nagpur (India) location, the optimum tilt angle for the installation of the system is found to be 20^o. The details of the calculations are discussed in Chapter 3 of this thesis.

6.2.3 Calculations for flux on the tilted surface [2]

Eq. (6.11), (6.12-6.19) was used to calculate the flux on the APV ssytem.

$$\frac{It}{Ig} = \left[1 - \frac{Id}{Ig}\right] rb + \left(\frac{Id}{Ig}\right) rd + rr \quad 6.12$$

$$r_b = \left(\frac{\cos\theta}{\cos\theta z}\right) \quad 6.13$$

$$r_d = (1 + \cos\beta)/2 \quad 6.14$$

$$rr = (1 - \cos\beta)/2 \quad 6.15$$

ASHRAE Model is used for components of hourly radiations as given in equations (6.16-6.19), [38]

$$I_b = Ig + Id \quad 6.16$$

$$I_b = Ibn \times \cos(\theta z) \quad 6.17$$

$$I_{bn} = A\exp[-(b/\cos\theta z)] \quad 6.18$$

$$I_d = C \times Ibn \quad 6.19$$

6.3 Estimation of land requirement and APV plant layout.

6.3.1 Effective module area

$$A_a = \text{Length} \times \text{Width} \quad 6.20$$

6.3.2 Area required for a single PV module

$$AR_S = L\cos\theta \times W \quad 6.21$$

6.3.3 Total base area required

$$AR_T = AR_S \times \text{Number of modules} \quad 6.22$$

6.3.4 Total area required

$$AR_P = 2 \times \text{Total Base Area} \quad 6.23$$

6.3.5 Calculations for Interrow spacing

The interrow spacing between the array was calculated as shown in Figure 6.3. [12]

Interrow distance of PV arrays,

$$\text{Spacing} = 3 \times \text{height} \quad 6.24$$

$$= 3 \times L\sin\theta \quad 6.25$$

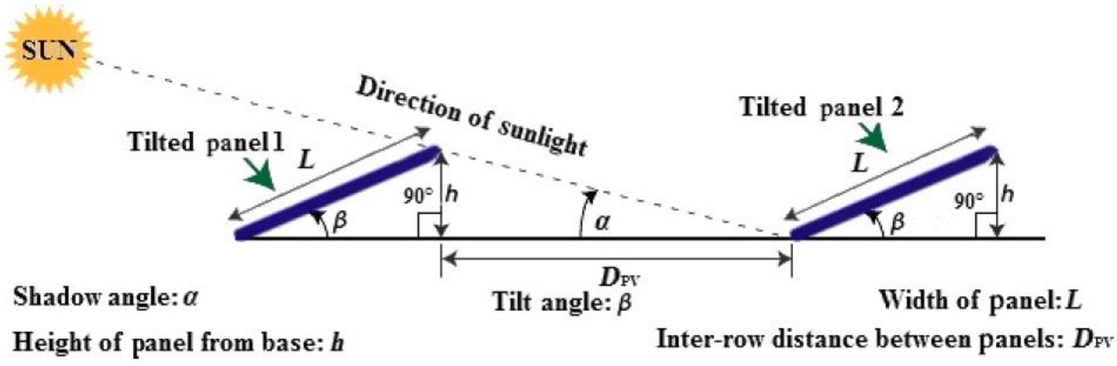


Fig. 6.3 Inter-row spacing of photovoltaic array. [12]

6.4 Estimation of PV module temperature with & without APV

According to the literature review [59], it has been found that the solar photovoltaic plant's output is significantly influenced by the radiation level and operating temperature of the PV module. Additionally, a number of studies have reported that the operating temperature of the PV module varies depending on the intensity of the radiation and the temperature of the environment. When predicting the operating temperature of a PV module, the most frequently used correlation is [61]

$$(T_{pv}) = 30 + 0.0175\,(Ig - 300) + 1.14(t_a - 25) \qquad 6.26$$

However, it has been observed that the equation 6.26 is based on the experimental studies carried out for different location and is framed using regression analysis. In the present work, the exhaustive experimental work is carried out and thus adequate observations have been recorded. Therefore, the same observation data has been used for the development of a new correlation for the estimation of PV temperature.

The correlations for the prediction of operating temperature of PV modules in conventional and APV systems have been developed in the current work. Based on the experimental studies for the duration of 9 months, experiments were conducted on both conventional PV plant and APV plant with three different crops. Utilizing accurately calibrated measuring tools, the irradiance, ambient temperature, and PV module temperature were all measured.

6.4.1 Regression Analysis

Regression analysis is a statistical technique that demonstrates the relationship between two or more variables. Multiple linear regressions employ a linear model to estimate the relationship between a quantitative dependent variable and two or more independent variables. In the present research work, a multilinear regression analysis was applied to determine the relationship between the independent variables viz; Ambient temperature (T_a), Irradiance (Ig) and Humidity (w) , and the dependent variable was temperature of PV module (Tpv). Considering these parameters the multilinear regression analysis was carried out to establish the relationship as shown in equation 6.27

$$(Tpv) = \beta 0 + \beta_1 Ig + \beta_2 Ta + \beta_3 w \qquad 6.27$$

Equation (6.27) estimates the value of temperature of PV module as well as the values of the regression coefficients, β_0, β_1, β_2 and β_3. As per the standard procedure, the error sum of squares (SSE) for each variable must be partially differentiated in order to estimate the regression coefficients, and it must be minimized. The SSE is represented in equation 6.28

$$SSE = \sum_{i=1}^{m} e_i^2 = e_1^2 + e_2^2 + \cdot \cdot \cdot + e_n^2 \qquad 6.28$$

where e_i represents the deviation of the regression estimation. The coefficient of determination (R^2) in a regression analysis is used to assess the goodness of fit or to determine the extent to which the independent variables can be used to estimate the dependent variable. The coefficient of determination (R^2) has been calculated using equation 6.29:

$$R^2 = \frac{\sum (\hat{y}i - \bar{y})}{\sum (yi - \bar{y})2} = \frac{\text{Variation explained by the regression line}}{\text{Total variation}} \qquad 6.29$$

where $(\hat{y}i - \bar{y})$ indicates the difference between the estimated dependent variable value and sample mean. The range of R^2 is $0 < R^2 < 1$. The value closer to 1 is considered as the best fit in the regression analysis. However, because multiple regression analysis involves two or more independent variables, it is important to take into account the adjusted coefficient of determination (Adjusted R^2). This corrects for the fact that R^2 begins to increase as the number of independent variables increases and is a necessary consideration in multiple regression analysis. Adjusted R^2 is estimated using the equation 6.30.

$$\text{Adjusted } R^2 = \frac{n-1}{(n-p-1)(1-R^2)} \quad 6.30$$

where $(n - p - 1)$ is the degree of freedom, n is the number of samples, and p is the number of independent variables.

For further confidence of statistical significance, the p-value and multicollinearity were determined. The R^2, adjusted R^2, and root mean square error (RMSE) values were used to assess the reliability of the regression model that was derived.

Vriance inflation factors (VIFs) VIFs was determined using Equation 6.31

$$VIF_i = \frac{1}{1-R^2} \quad 6.31$$

The variable has multicollinearity if the VIF is higher than 10, so it should be left out of the regression analysis. When comparing the differences between estimated and measured values, the RMSE is frequently used and is a good way to express precision.

6.5 Correlations by regression analysis

For the purpose of multilinear regression analysis, 'Minitab' statistical tool has been used. As mentioned in the section 6.4.1, the PV module temperature (Tpv) is considered as dependent parameter and the other three parameters viz; Ambient temperature (Ta), irradiance (Ig), and humidity (ω) were considered as independent variables. The experimental data obtained by the 9 months of experiments was considered, the data was sorted considering the suitable significant data by removing the outliers. The multilinear regression process as given by Minitab guidelines was followed and the analysis was carried out. The consolidated statistics of the regression model obtained by the MINITAB tool has been shown in table 6.1.

Table 6.1 The outcomes of the regression analysis

Case	Const.	Ta	Ig	ω	S	R^2	Adj. R^2	Pred. R^2
Aloe Vera Height-I Conv.	8.40	0.7263	0.01882	-0.204	2.03537	0.9313	0.9283	0.9238
Aloe Vera Height-I APV	13.11	0.5612	0.01782	-0.0959	2.09018	0.923	0.9196	0.9137
Aloe vera Height-II Conv.	23.99	0.3974	0.01722	-0.1063	2.43451	0.8781	0.8727	0.8643
Aloe vera Height-II APV	19.72	0.4638	0.01090	-0.0841	1.84345	0.8812	0.8760	0.8671
Spinach Height-I Conv.	26.56	0.368	0.01761	0.1862	2.56680	0.8940	0.8893	0.8811
Spinach Height-I APV	13.62	0.597	0.01600	-0.1278	2.23684	0.9127	0.9089	0.9022
Spinach Height-II Conv.	53.2	0.8188	0.015396	0.0519	1.84539	0.9298	0.9267	0.9212
Spinach Height-II APV	1	0.8118	0.01526	0.0512	2.04499	0.9138	0.91	.09048
Tomato Height-I Conv	-7.39	1.206	0.00951	0.1086	2.66435	0.8380	0.8309	0.8169
Tomato Height-I APV	-11.70	1.187	0.00825	0.1678	3.06007	0.7616	0.7511	0.7340
Tomato Height-II Conv.	2.61	0.807	0.01722	0.0630	2.47260	0.8686	0.8628	0.8520
Tomato Height-II APV	8.38	0.618	0.01578	0.0320	2.48487	0.8417	0.8347	0.8220

Based on the obtained values of regression coefficients, the correlations for the PV module temperatures are obtained as shown in equations 6.32 to equations 6.43 as below

6.5.1 Correlations for Aloe Vera for Height-1

For conventional PV plant

Regression Equation in Uncoded Units

Tpv conv Exp = 8.40 + 0.7263 Ta + 0.01882 Ig - 0.0204 W 6.32

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
2.03537	93.13%	92.83%	92.38%

For APV plant

Regression Equation in Uncoded Units

Tpv APV Exp = 13.11 + 0.5612 Ta + 0.01782 Ig - 0.0959 W 6.33

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
2.09018	92.30%	91.96%	91.37%

6.5.2 Correlations for Aloe Vera for Height-2

For conventional PV plant

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
2.43451	87.81%	87.27%	86.43%

Regression Equation in Uncoded Units

Tpv conv Exp =23.99 + 0.3974 Ta + 0.01722 Ig - 0.1063 W 6.34

For APV plant

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
1.84345	88.12%	87.60%	86.71%

Regression Equation in Uncoded Units

Tpv APV Exp = 19.72 + 0.4638 Ta + 0.01090 Ig - 0.0841 W 6.35

6.5.3 Correlations for Spinach for Height-1

For conventional PV plant

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
2.56680	89.40%	88.93%	88.11%

Regression Equation in Uncoded Units

Tpv conv Exp = 26.56 + 0.368 Ta + 0.01761 Ig - 0.1862 W 6.36

For APV plant

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
2.23684	91.27%	90.89%	90.22%

Regression Equation in Uncoded Units

Tpv APV Exp = 13.62 + 01.597 Ta + 0.01600 Ig - 0.1278 W 6.37

6.5.4 Correlations for Spinach for Height-2

For conventional PV plant

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
1.84539	92.98%	92.67%	92.12%

Regression Equation in Uncoded Units

Tpv conv Exp = 5.32 + 0.8188 Ta + 0.015396 Ig + 0.0519 W 6.38

For APV plant

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
2.04499	91.38%	91.00%	90.48%

Regression Equation in Uncoded Units

Tpv APV Exp = 1.00 + 0.8118 Ta + 0.01526 Ig + 0.0512 W 6.39

6.5.5 Correlations for Tomato for Height-1

For conventional PV plant

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
2.66435	83.80%	83.09%	81.69%

Regression Equation in Uncoded Units

Tpv Conv Expt = -7.39 + 1.206 Ta + 0.00951 Ig + 0.1086 W 6.40

For APV plant

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
3.06007	76.16%	75.11%	73.40%

Regression Equation in Uncoded Units

Tpv APV Expt = -11.70 + 1.187 Ta + 0.00825 Ig + 0.1678 W 6.41

6.5.6 Correlations for Tomato for Height-2

For conventional PV plant

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
2.47260	86.86%	86.28%	85.20%

Regression Equation in Uncoded Units

Tpv conv Exp = 2.61 + 0.807 Ta + 0.01722 Ig + 0.0630 W 6.42

For APV plant

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
2.48487	84.17%	83.47%	82.20%

Regression Equation in Uncoded Units

Tpv APV Exp = 8.38 + 0.618 Ta + 0.01578 Ig + 0.0320 W 6.43

The temperatures so obtained by the regression models were compared with the actual values observed in the experimental studies. Fig. 6.4 shows the comparison between the predicted values of module temperature and the module temperatures as obtained by the regression model as a sample.

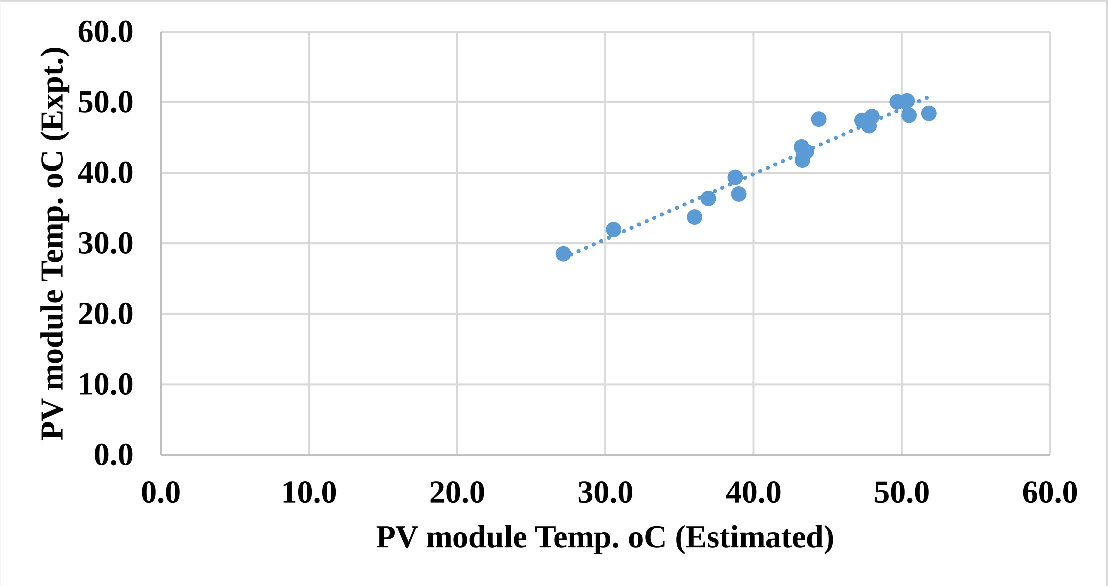


Fig. 6.4: Comparison between theoretical and experimental results

As shown in fig. 6.4 the predicted values and values by the regression analysis matches with each other.

6.6 Power output of the PV system

Equation. 6.44 was used to estimate the power output of the solar PV module based on the temperature coefficient and the module temperature

Poutput = (Pstc/1000)*IT-(Temp Coeff.(Tpv-25)*Pstc) 6.44

The solar PV modules of same specifications as used in the experimental study has been considered which are of capacity 330 Wp of make Luminious having the temperature coefficient of power is -0.3677%/^{o}C.

Subsequently the electrical units generated by the conventional PV plant and the APV plant were estimated.

6.6.1 Estimation of electrical output by the conventional and APV plant for Spinach Height-I

The estimated power output of the APV plant and the conventional PV plant are compared with the experimental results in Fig. 6.5. And the fig 6.6 compares the units produced by the conventional and APV plants based on experimental findings and theoretical estimations.

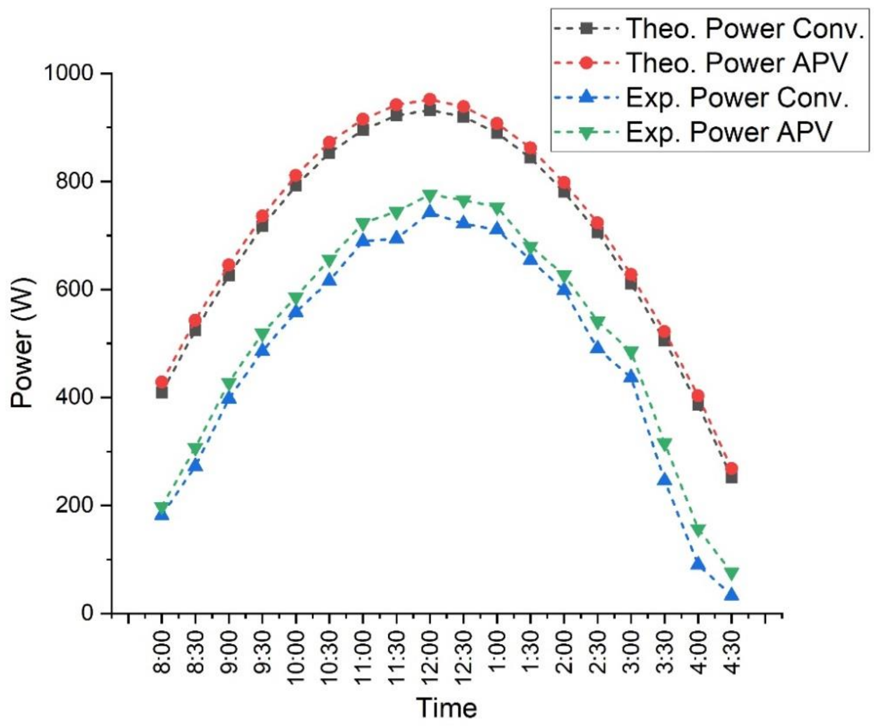


Fig. 6.5: Power output of Conventional and APV system (Experimental & Theoretical) Spinach Height-I

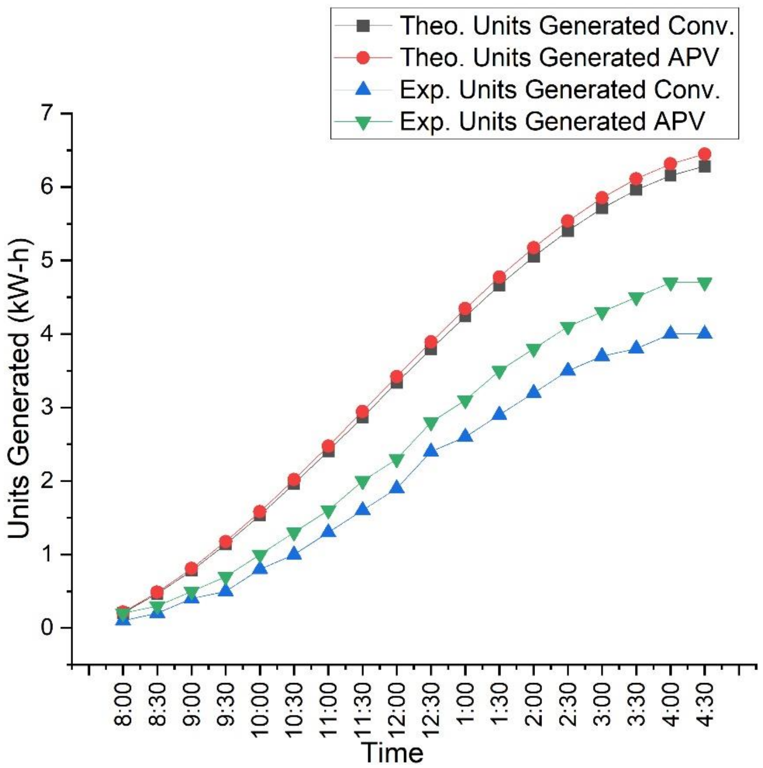


Fig. 6.6: Units Generated of Conventional and APV system (Experimental &

Theoretical) Spinach Height-I

As shown in fig. 6.5 and fig. 6.6, the experimental values of power output and the electricity units generated are matching with the theoretical estimation.

6.6.2 Estimation of electrical output by the conventional and APV plant for Spinach Height-II

The estimated power output of the APV plant and the conventional PV plant are compared with the experimental results in Fig. 6.7. and the fig 6.8 compares the units produced by the conventional and APV plants based on experimental findings and theoretical estimations

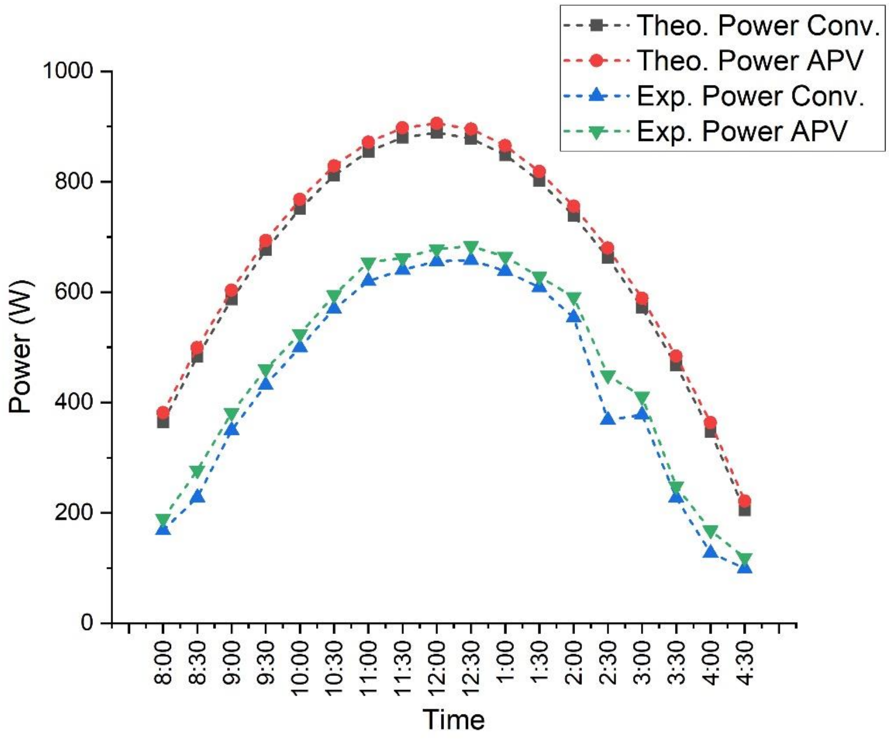


Fig. 6.7: Power output of Conventional and APV system (Experimental & Theoretical) Spinach Height-II

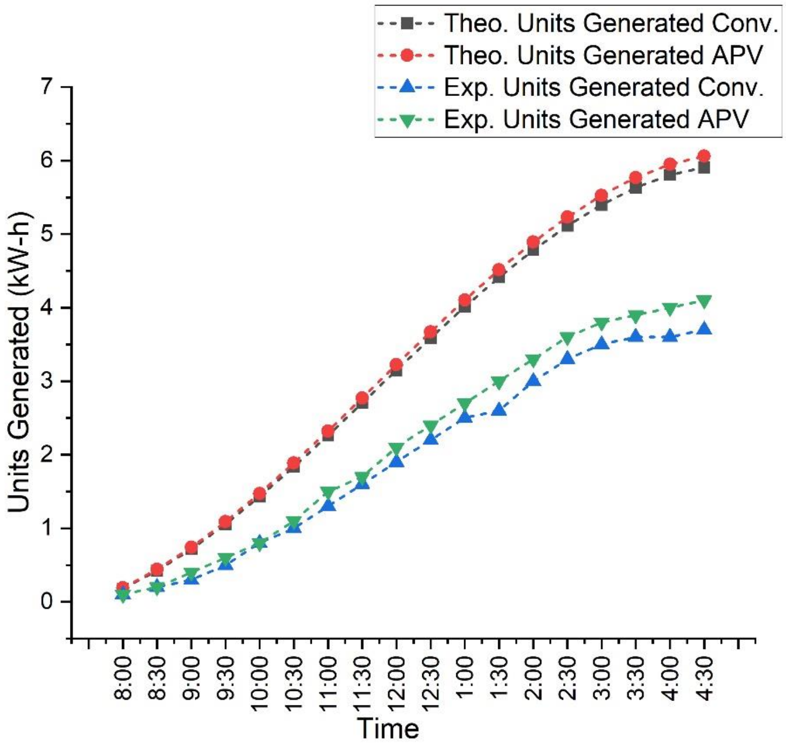


Fig. 6.8: Units Generated of Conventional and APV system (Experimental & Theoretical) Spinach Height-II

As shown in fig. 6.7 and fig. 6.8, the experimental values of power output and the electricity units generated are matching with the theoretical estimation.

6.6.3 Estimation of electrical output by the conventional and APV plant for Tomato Height-I

The estimated power output of the APV plant and the conventional PV plant are compared with the experimental results in Fig. 6.9. and the fig. 6.10 compares the units produced by the conventional and APV plants based on experimental findings and theoretical estimations

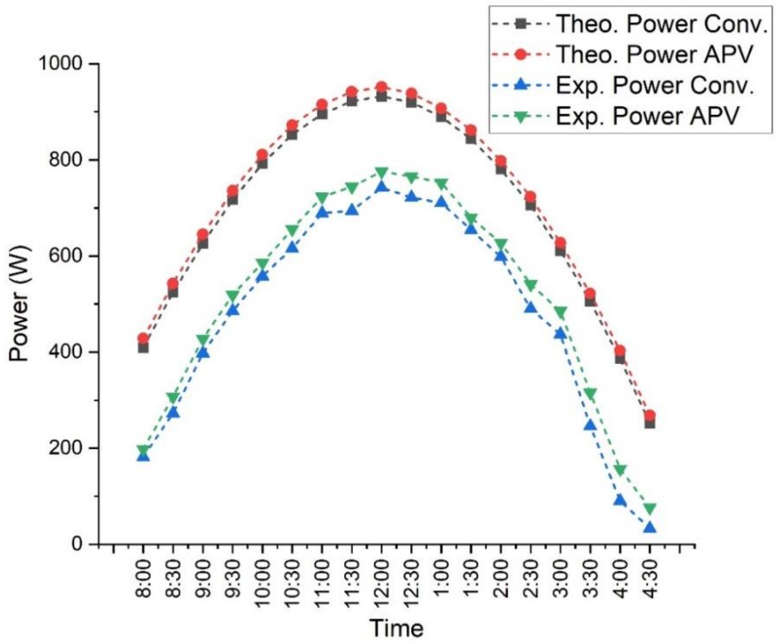


Fig. 6.9: Power output of Conventional and APV system (Experimental & Theoretical) Tomato Height-I

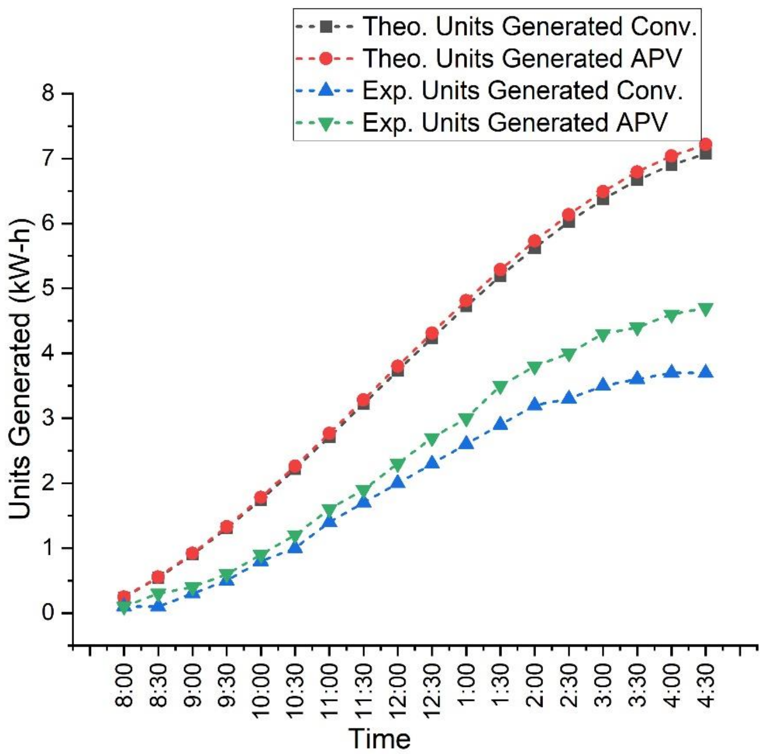


Fig. 6.10: Units Generated of Conventional and APV system (Experimental & Theoretical) Tomato Height-I

As shown in fig. 6.9 and fig. 6.10, the experimental values of power output and the electricity units generated are matching with the theoretical estimation.

6.6.4 Estimation of electrical output by the conventional and APV plant for Tomato Height-II

The estimated power output of the APV plant and the conventional PV plant are compared with the experimental results in Fig. 6.11. and the fig. 6.12 compares the units produced by the conventional and APV plants based on experimental findings and theoretical estimations

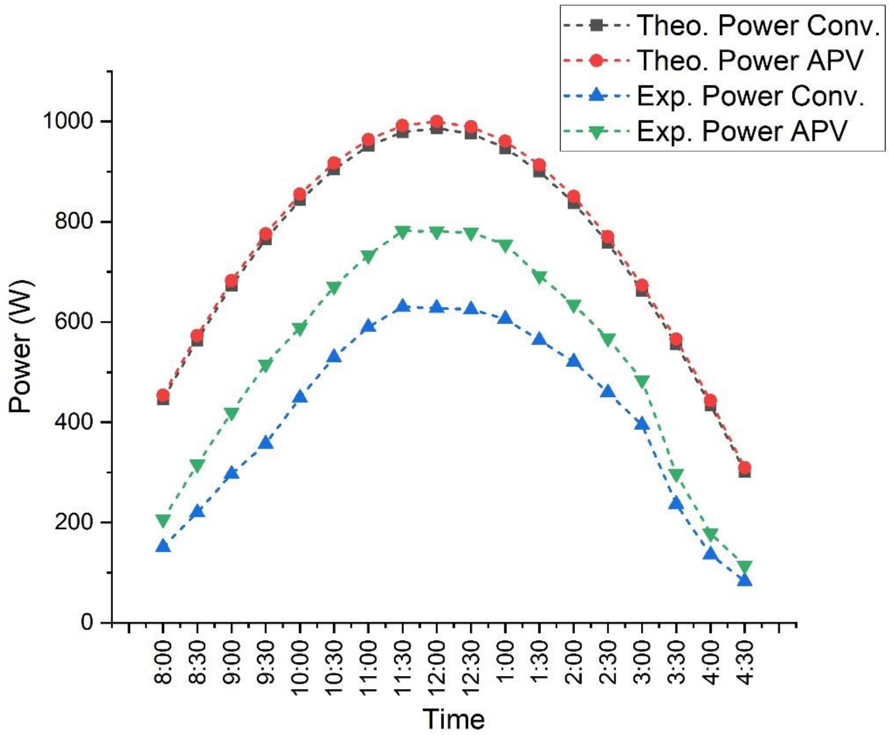


Fig. 6.11: Power output of Conventional and APV system (Experimental & Theoretical) Tomato Height-II

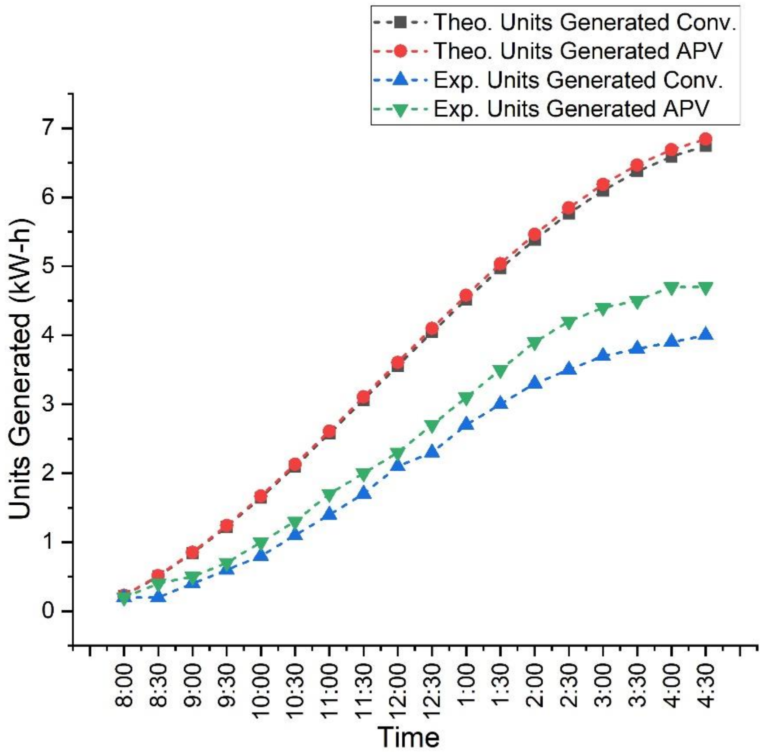


Fig. 6.12: Units Generated of Conventional and APV system (Experimental & Theoretical) Tomato Height-II

As shown in fig. 6.11 and fig. 6.12, the experimental values of power output and the electricity units generated are matching with the theoretical estimation.

6.6.5 Estimation of electrical output by the conventional and APV plant for Aloe Vera Height-I

The estimated power output of the APV plant and the conventional PV plant are compared with the experimental results in Fig. 6.13 and the fig. 6.14 compares the units produced by the conventional and APV plants based on experimental findings and theoretical estimations

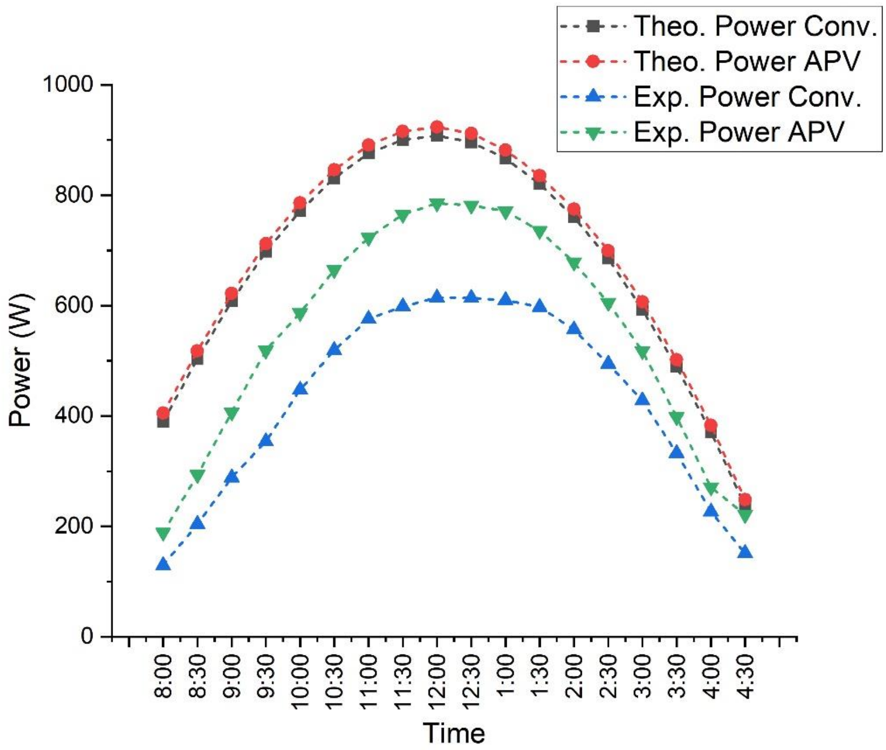


Fig. 6.13: Power output of Conventional and APV system (Experimental & Theoretical) Aloe Vera Height-I

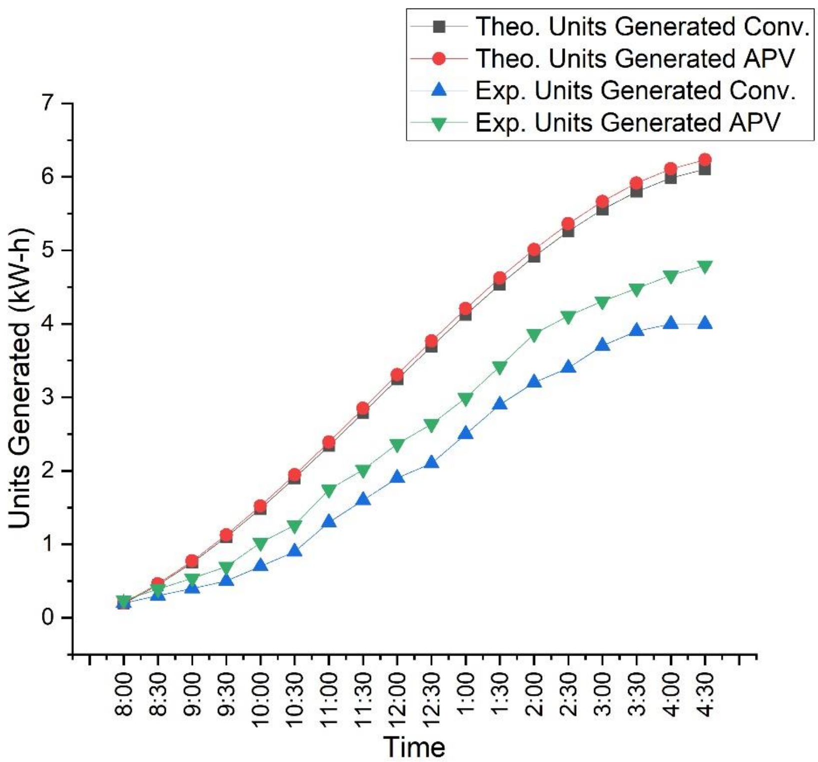


Fig. 6.14: Units Generated of Conventional and APV system (Experimental & Theoretical) Aloe Vera Height-I

As shown in fig. 6.13 and fig. 6.14, the experimental values of power output and the electricity units generated are matching with the theoretical estimation.

6.6.6 Estimation of electrical output by the conventional and APV plant for Aloe Vera Height-II

The estimated power output of the APV plant and the conventional PV plant are compared with the experimental results in Fig. 6.15 and the fig. 6.16 compares the units produced by the conventional and APV plants based on experimental findings and theoretical estimations

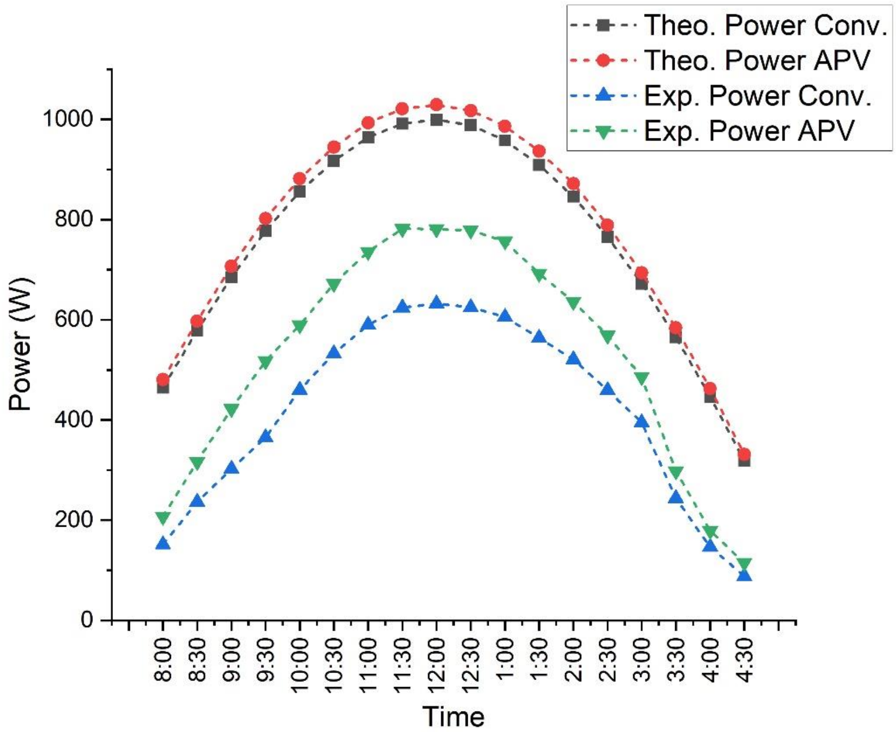


Fig. 6.15: Power output of Conventional and APV system (Experimental & Theoretical) Aloe Vera Height-II

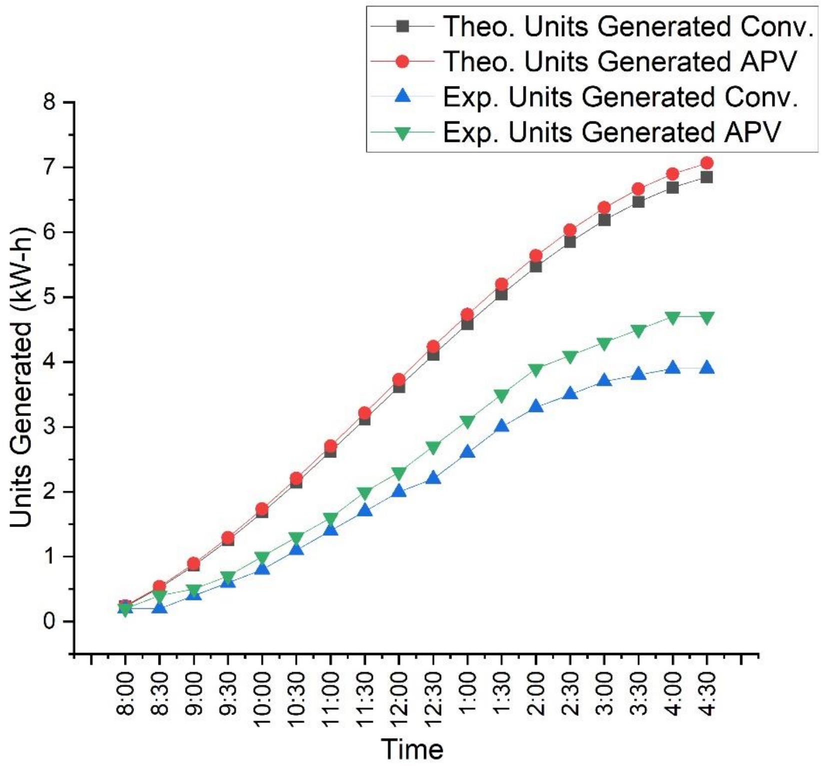


Fig. 6.16: Units Generated of Conventional and APV system (Experimental & Theoretical) Aloe Vera Height-II

As shown in fig. 6.15 and fig. 6.16, the experimental values of power output and the electricity units generated are matching with the theoretical estimation.

Overall, the theoretical model developed in this study shows an output that is consistent with experimental results for power generation by APV and conventional power plants. Therefore, the developed theoretical model can be used to forecast the performance of the APV plant for any given location considering the electrical parameters of the PV module, angle of inclination and meteorological parameters.

Chapter-7

Discussions and Conclusions

This chapter presents the key findings from the current research work. The overview of the research is presented in the first section of the chapter, which is followed by a discussion of the key findings. The various aspects of the APV system that are outlined based on the current study are highlighted in the second section of the chapter. The chapter concludes with an overview of the future research scope to develop the large scale APV systems.

7.1 Outline of the present study

Agrophotovoltaics, also known as Agrivoltaic (APV), is the practice of using the same plot of land for both agricultural purposes and the production of electricity using solar PV modules. The current study aimed to investigate the performance of the APV and compare it to the conventional systems of independent solar PV plant and agricultural farm. During the present study, a state-of-the-art experimental setup was designed and installed at Nagpur as a 2 kW grid-connected solar PV plant. Half of the PV plant was used as a conventional power plant, while the other half was converted to an APV farm by cultivating the crops beneath the PV modules. The experiments were carried out over a 9-month period from march to July, using three different crops viz; Aloe Vera, Spinach, and Tomato. Individual crop yields were measured in comparison to open sky farming. Through a series of experiments, the effect of each of these crops on the thermal and electrical performance of the solar PV module was investigated. The effect of different heights of the solar PV module in an APV system was also thoroughly investigated. Furthermore, a systematic theoretical model has been developed to estimate the performance of the APV plant for any given location and any type of PV module. The important findings of these studies are reported in the following paragraphs.

7.2: The significant findings of the present research work

The following paragraphs explains the significant findings of the present research work

7.2.1 Effect on the module temperature in APV system

In the APV system the crops are cultivated in the inter-row spacing and or beneath the solar PV module. In the present research work the crops were cultivated beneath the solar PV module. Most crops have some capacity for transpiration, which allows them to cool and reduce the temperature of their surroundings.

Transpiration is one of the most important physiological processes that plants undergo, as it influences the temperature of their surroundings when exposed to sunlight. Water emerges from the leaf's surface through transpiration when solar energy hits it, absorbing the latent heat and converting it to water vapor. As a result, the atmosphere's humidity rises and the temperature of the leaf falls. To maintain equilibrium, the leaf absorbs heat from the surrounding atmosphere, lowering the ambient temperature. This property of the crops is beneficial to reduce the PV module temperature in the APV system. This reduction in the PV module temperature was evident in the present experimental studies.

According to the findings from the experimental studies, the average reduction in module temperature in the APV system was around 12.23% when compared to the conventional PV power plant. The maximum reduction in the PV module temperature was observed for the Tomato crops among the three selected crops in the present study.

7.2.2 Effect on the Electrical Output of the PV system in APV

When the solar cell is exposed to sunlight, the photons other than its response range are getting absorbed in the solar cell material. This leads to elevate the operating temperature of the solar cells. The output of the solar cell reduces with increasing cell temperature. As discussed in section 7.2, the APV system are beneficial to reduce the PV module temperature thereby the electrical output of the PV system increases.

In this study, the power output of the PV system was increased by 7.27% on average when compared to the conventional power plant. When considering the MW capacity plant, the increase in power output of the Solar PV plant is significant. According to the current study's findings, the increase in energy units generated by the 1 MW APV plant over the conventional power plant is approximately 168594 kWh/year

7.2.3 Effect on the height of the PV module on the output of the APV system

As discussed in section 7.2, transpiration cooling by crops reduces module temperature and thus improves the electrical output of the PV modules in APV system. The effect of different PV module heights on output was also investigated in the present experiential studies. The two heights of the PV modules from the ground, 1m and 1.5m, were considered. When the gap between the back surface of the PV module and the cultivated crop is smaller, the APV plant would be more beneficial in terms of electrical output. The same fact was evident in the experimental study; the temperature of the PV module was reduced more in the case of 1 m module height than in the case of 1.5 m module height.

7.2.4 The crop yield in APV system

The selection of the most suitable crops is one of the crucial aspects of APV systems. The shade tolerant crops are considered as the first choice for the APV system. There are several such crops are cultivated in the region of experimental study. The list of such crops has been given in chapter 2 of this thesis.

During the current experimental study, it was discovered that crop growth beneath the PV module was comparable to that of open sky conventional farm. And, in particular, for Aloe Vera crops, the overall growth of the crop (the density of the cultivated crop) was greater in the case of the APV system than the open sky farming.

7.2.5 The Land equivalent ratio (LER)

Land Equivalent Ratio (LER) is used to quantify the land use efficiency. LER is defined as the ratio of total yield by dual production (Electricity + Crop yield) to the crop yield alone LER <1 indicates that the APV system is less productive than separate production. On the other hand, LER >1 indicates increased productivity in the APV system as compared to the crop production alone. In the current study, the LER was calculated for all crops and found to be greater than 1. This clearly demonstrates the APV system's effectiveness.

7.2.6 The theoretical model for the performance estimation of APV system

A comprehensive theoretical model was developed using a sematic methodology in the present work to estimate the performance of the APV plant for any given location and PV module type. The model is based on the standard correlations used to estimate the irradiance at the given location, optimum tilt angle and the derived correlations for the estimation of module temperature based on the experimental data as found by the multi linear regression analysis carried out using Minitab tool. The model accurately predicts the APV plant's performance as explained in the chapter 6. The model would be useful for predicting the performance of the APV plant for any given location prior to its actual installation.

7.3: Various Aspects of the APV system for its large-scale deployment

APV systems are still in their inception, with ample space for technical advancements and new potential applications. Based on the entire research work conducted in this study, several aspects of the APV system have been identified for its large-scale deployment. Some of the important points are discussed in the following text.

- **Selection of suitable crops**

To avoid a negative impact on agricultural production, specific crop selection is so much more crucial in the APV system. Because of the PV panels, there will be ample shade below the panels and in the inter row spaces to affect plant growth. To avoid this shading effect, it is essential to maintain the spacing between two arrays and elevate the PV modules to appropriate height. Crops grown in the shade, on the other hand, necessitate the selection of suitable crops with a substantial level of shade tolerance. The crops that are suitable for APV are thoroughly discussed along with the selection criteria in Chapter 2 of this thesis. Crops with a low height, shade tolerant and a low water requirement are suitable for APV.

- **Selection of suitable mounting structure**

The design and array configuration of solar PV modules create a major impact on farmland insolation so it is essential to optimize the structure of solar panel installation. Solar panels are oriented in the fixed south-facing direction in northen hemisphere, but literature reveals that the east-west tracking provides better shade tolerance. To allow typical agricultural machinery to pass, the PV panels must be lifted to an adjusted overhead clearance. The distance between the panel columns should be maintained sufficiently for the crop cultivation and driving of machinery. The height of the crop is an important factor APV system as the tall-growing plant may create shade on the solar panels and thus lowers the power generation.

- **Crop cultivations in inter-row spacing and beneath the modules**

Crops are planted in the interspaces between PV arrays and beneath the PV arrays in APV systems. The cropping area varies depending on the design of the installation. The interspace and below PV module areas suitable for crop cultivation in a typical Agrivoltaic system are approximately 49% and 24% of the total block area, respectively. Therefore the proper design and layout of the APV plant is one of the most important aspects.

- **Static and tracking PV modules**

The shading levels of the crops can be dynamically regulated by rotating the PV modules around fixed axes to change the amount of shadowing in the greenhouse. For both agriculture and electricity generation, such tracking systems provide greater flexibility in light management. Static, one-axis tracking and two-axis tracking are the innovative techniques those can be adopted for the APV system for better performance.

7.4: Directions for future research

The APV systems are very useful for better land utilization for electricity generation and farming simultaneously. Many investigators have been working on the APV systems since its inception across the globe. However, most of the work is aimed at giving proof of the concept using simulation techniques or trivial experimental work. Moreover, despite having one of the solar resource-rich tropical countries, having around 16% share on the world population, very little APV development has been observed in India. Owing to this, to promote APV systems some of the future research directions have been discussed in the subsequent paragraphs.

- **Experimental work**

The development of the APV system is in the nascent stage. As mentioned, very little experimental work has been reported on the APV system so far. The performance of the APV systems depends on several aspects as discussed in the present study. The simulation methods can predict the system performance considering most of these aspects; however, the field experimentations are essential to understand the performance of APV systems and their better dissemination in society. Some of the significant aspects that need experimentation are the selection of crops suitable for the geographic and climatic conditions, selection of PV technology, selection of the PV module mounting structure, effect of mounting height and inter-row spacing, space between the crop and PV module, light transmission for crop cultivation, the requirement of light during developmental phases of crops, evapotranspiration cooling of PV modules, etc.

- **Hydroponic APV systems**

Hydroponics refers to crop cultivation using mineral nutrient solutions without soil. Thus, hydroponic farming gives a new way for water conservation in farming. Hydroponic farming can be clubbed with the APV systems, wherein the shade-tolerant hydroponic crops can be cultivated in the inter-row spaces and beneath the solar PV modules similar to conventional APV systems. Furthermore, the wastewater of the PV module cleaning system can be used by the hydroponic crops. In addition, the hydroponic crops can be cultivated in the pipes attached to the mounting structure of the solar PV plant thereby leaving the footprint land assessable for conventional farming. Experimental work is required to check the feasibility of hydroponic APV systems.

- **Rainwater harvesting from the APV system**

Rainwater harvesting is the most sustainable way to store the water for supplementary irrigation. Several lac hectares of crops are getting damaged in India due to heavy rainfall. During undesired rain, there is no option to safeguard the crops in conventional farming. The APV system can be one of the solutions to this problem; the undesirable rain can be harvested from the PV modules and can be stored in the appropriate cisterns for irrigation or other purposes. The techno commercial aspects of this proposition have to be investigated for various potential locations.

- **Evapotranspiration in APV systems**

It has been a well-accepted fact that solar PV modules can perform better at lower operating temperatures. The crops cultivated in the APV system can help to lower the operating temperature of the PV modules by evapotranspiration. This aspect of the APV system has not been explored much. The experimental study carried out in the present study shows the potential benefits of evapotranspiration cooling by crops in the APV systems. However, it is essential to investigate this effect thoroughly to identify more avenues to improve the evapotranspiration cooling and crop yield simultaneously. It is essential to develop a detailed model of evapotranspiration in the APV system that can incorporate the effects specific type of crop, climatic factors, vapour pressure deficit, sensible and latent heat loads by different plant varieties, sensible heat ratios on the cooling potential of the photovoltaic modules of APV systems.

- **Roof-mounted APV systems**

Most of the APV studies available in the literature are on ground-mounted systems only, however, the roof-mounted PV installations from 1 to 5 kW are getting popular throughout the world. The space below the PV module on the rooftop is generally unutilized. The roof-mounted APV systems can enjoy multiple benefits like improved electrical power output due to the evapotranspiration effect, conventional rooftop gardens, and hydroponic rooftop gardens. Furthermore, the rooftop APV systems can be beneficial to lower the roof temperature further.

List of Publications based on the Ph. D work

Journals: Paper- 1

- Rahul Waghmare, Ravindra Jilte, Sandeep Joshi, ‘Review on Agrophotovoltaic systems with a premise on thermal management of photovoltaic modules therein’ published at Environmental Science and Pollution Research on 28 September 2022. **(SCI indexed)**

  https://doi.org/10.1007/s11356-022-23202-6

Environmental Science and Pollution Research
https://doi.org/10.1007/s11356-022-23202-6

SUSTAINABLE RESEARCH FOR ENERGY AND ENVIRONMENT

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Review on agrophotovoltaic systems with a premise on thermal management of photovoltaic modules therein

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Received: 20 September 2021 / Accepted: 19 September 2022

Abstract

Agrophotovoltaics (APV) is the coexistence of solar photovoltaics (PV) and agriculture on the same piece of land. Although the concept of APV is known for the last two decades, its actual penetration in society is inconsiderable. The objective of the current article is to discuss the various APV systems explored in the past and to highlight the futuristic APVs. Furthermore, this study presents the review of the available experimental work on the performance and environmental and techno-economic aspects of the APV systems. The key features, crop selection criteria, feasible crops for Indian climatic conditions, and the future research directions of APV systems have been summarized. Furthermore, apart from the known techno-economic benefits of APV, a premise on its another utility for the thermal management of the solar PV modules by crops' natural transpiration cooling has been presented in this study. A theoretical study demonstrates the gain in the electrical output of the solar PV plant as compared with the conventional PV installation. The theoretical study has been carried out considering the meteorological data of Nagpur (21.1458° N, 79.0882° E). The estimation has been carried out using Nominal Operating Cell Temperature (NOCT) model, NREL irradiance database—NSRDB, and System Advisor Model (SAM). An experimental study has been conducted on APV systems with a 2-kW solar PV plant and tomato crops to investigate its actual performance. The study shows an increment of 17.96% in the daily energy generation as compared with the conventional solar PV power plant.

Keywords Agrivoltaics · Agrophotovoltaics · APV · Thermal management of PV · Transpiration cooling · Greenhouse APV

Introduction

Solar photovoltaic systems are being considered the most competitive option for electricity generation. Solar photovoltaic installations are increasing at a rapid pace. On the other hand, due to the limited efficiency of the solar photovoltaic modules, a lot of land space will be required for their installation. Considering the present efficiency of the commercial polycrystalline solar PV modules, a 1-MW plant requires about 4 acres of land. On the other hand, the increasing population and urbanization are causing the scarcity of arable land throughout the world. Thus, a tough land-use competition has been envisaged in the near future. Utilizing the same piece of land for crop cultivation and installation of solar photovoltaic modules can be the best solution for the above-mentioned problem. This coexistence of crops and the solar photovoltaic modules is known as "agrivoltaic" or "agrophotovoltaics" (APV).

Concept of agrophotovoltaics

Agrophotovoltaics (APV), also known as agrivoltaics, was introduced by German physicists Adolf Goetzberger and A. Zastrow in 1981 (Goetzberger and Zastrow 2015). The typical solar photovoltaic plant has several solar photovoltaic modules connected in multiple strings. The appropriate inter-row spaces are provided in between these strings. Furthermore, for better ventilation and access, the solar photovoltaic modules are mounted at a certain height from the

Communicated by: Philippe Garrigues

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Published online: 28 September 2022

Springer

Paper- 2

- Rahul Waghmare, Ravindra Jilte, Sandeep Joshi 'Performance analysis of Agrophotovoltaic systems with Solanum Lycopersicum crops' published at Materials Today: Proceedings on 28 September 2022. **(SCOPUS indexed)** https://doi.org/10.1016/j.matpr.2022.09.300

Materials Today: Proceedings xxx (xxxx) xxx

Contents lists available at ScienceDirect

Materials Today: Proceedings

journal homepage: www.elsevier.com/locate/matpr

Performance analysis of Agrophotovoltaic systems with Solanum lycopersicum crops

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A R T I C L E I N F O

Article history:
Available online xxxx

Keywords:
Agrivoltaic
Agrophotovoltaic
APV
Photovoltaic
Energy

A B S T R A C T

The coexistence of solar photovoltaics (PV) and agriculture on the same piece of land is known as Agrophotovoltaics (APV). Along with a few additional advantages, APV systems are presently being investigated for the thermal control of solar PV modules using natural transpiration cooling from crops. In the present work, an experimental setup of a grid-connected rooftop solar PV system of 2.0 kW was designed, developed, and installed at Nagpur [21° 08′ N, 46.72″ E] India. The Solanum lycopersicum plants commonly known as 'Tomato' were cultivated below the 50 % solar PV modules to convert the half PV power plant into an Agrophotovoltaic system. The experiments were performed to compare the electrical and thermal performance of the conventional solar PV plant and the APV plant for one month. Along with the power plant's performance, the overall growth of tomato crops was also monitored throughout experiments. The experiments conclude that as compared with the conventional solar PV system, the temperature of the solar PV modules in the APV system reduces by around 6.51 %lower for the height-I whereas for height –II the module temperature of APV system was lower by around 3.12 % and the power output increases by17.96 % more energy for height-I whereas for height-II the APV plant generates 14.70 % more energy per day. Also, it had been observed that the growth of the cultivated tomato crops in the APV was the same as that of the crop grown in the open sky. Based on the current experimental research, a 1 MW APV system's expected yearly electricity generation would be 215,520 kWh higher than a normal solar PV plant for height-I and1 76400 kWh more electricity for height-II. Furthermore, in addition to the bonus of increased power generation, the same piece of land would be used to produce tomato or other high-yielding crops.

Selection and peer-review under responsibility of the scientific committee of the 2nd International Conference and Exposition on Advances in Mechanical Engineering.

1. Introduction

Solar photovoltaic systems are thought to be the most cost-effective way to generate electricity. Solar photovoltaic systems are rapidly expanding. Due to the low efficiency of solar photovoltaic modules, however, a large amount of land space will be required for their installation. Considering the present efficiency of the commercial polycrystalline solar PV modules, a 1 MW plant requires 4 acres of land. On the other side, the world's growing population and urbanization are generating a global shortage of arable land. As a result, a fierce land-use rivalry is expected in the near future. The ideal answer for the above-mentioned difficulty may be to use the same piece of land for crop production and solar photovoltaic module installation. This coexistence of crops and the solar photovoltaic modules is known as 'Agrivoltaic' or 'Agrophotovoltaics (APV)'.

2. Concept of agrophotovoltaics

In 1981, German physicists Adolf Goetzberger and A. Zastrow created agrophotovoltaics (APV), also known as Agrivoltaics [10]. The typical solar photovoltaic plant has several solar photovoltaic modules connected in multiple strings.

The appropriate inter-row spaces are provided in between these strings. Furthermore, for better ventilation and access, the solar photovoltaic modules are mounted at a certain height from the ground. Also, the modules are mounted at optimum tilt angle to

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https://doi.org/10.1016/j.matpr.2022.09.300
2214-7853/
Selection and peer-review under responsibility of the scientific committee of the 2nd International Conference and Exposition on Advances in Mechanical Engineering.

Paper- 3

- Rahul Waghmare, Ravindra Jilte, Sandeep Joshi, 'Investigations on Agrophotovoltaic System Using Different Crops with Special Attention on the Improved Electrical Output', published at Applied Science and Engineering Progress, Vol. 17, No. 2, 2024, 7014, **(SCOPUS indexed)**, DOI: 10.14416/j.asep.2023.09.007

Applied Science and Engineering Progress, Vol. 17, No. 2, 2024, 7014 1

Research Article

Investigations on Agrophotovoltaic System Using Different Crops with Special Attention on the Improved Electrical Output

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Received: 6 May 2023; Revised: 18 June 2023; Accepted: 9 August 2023; Published online: 25 September 2023

Abstract
In an Agrophotovoltaic (APV) system, the same plot of land is used for both agriculture and power production. APV systems are currently being investigated for thermal control of solar PV modules using natural transpiration cooling by cultivated crops. The current research focuses on the experimental studies on a 1 kWp APV and 1 kWp reference system with two different crops cultivated beneath the solar PV modules; an experimental setup was designed and built in Nagpur, India. Two crops, *Spinacia oleracea* and *Solanum lycopersicum* (Spinach and Tomato, respectively), were grown below 50% of PV modules, and the thermal and electrical performance of the solar plant was investigated as an APV system. The performance of this APV system was compared with the remaining 50% of PV installation. During this study, the effect of crop height on the performance of the solar plant was also investigated. According to the experiments, the temperature of the solar PV modules in the APV system with Tomato and Spinach was reduced by about 5 °C and 6 °C, respectively, when compared to a reference solar PV system. Additionally, the power plant's production is higher when there is less space between the solar PV module and the crop. To predict the performance of the APV system for any given location and for any given crops a systematic analytical procedure has been formulated. This experimental study shows that for the spinach and tomato crops, a 1 MW APV system would produce 169200 kWh and 187500 kWh more electricity yearly than a reference solar PV plant, respectively. Additionally, the same piece of land would give a comparable crop yield along with improved power generation.

Keywords: Agrophotovoltaic, Agrivoltaic system, Crop cultivation, Green energy, Solar photovoltaic module

1 Introduction

Solar photovoltaics is the most competitive option for electricity generation today, and it is being rapidly explored in every corner of the globe [1]. The standardized manufacturing technique, competitive pricing, and active government support have resulted in large-scale PV deployment around the world. [2] However, a new challenge—a severe land-energy conflict—is envisioned in the near future, leaving aside the other challenges like PV system's high cost, low efficiency, and recycling or disposal. [3] The solution to this problem could be to combine the production of electricity and agriculture on the same plot of land with an agrivoltaic system. Agrivoltaic System refers to the use of land for both agriculture and electricity generation (APV) [4].

Although the concept of an agrophotovoltaic system has been understood for more than 20 years, its real penetration in society, especially in India, is low as a result of a lack of research on numerous elements and a lack of awareness [5]. The research

International Conference-1

- Rahul Waghmare, Ravindra Jilte, Sandeep Joshi, Pranjali Tete, 'Review on agrophotovoltaic systems with a premise on thermal management of photovoltaic modules therein' Proceedings of International Conference on Advances in Sustainable Research for Energy and Environmental Management (ASREEM-2021) August 06-08, 2021 (Paper ID: ASIN0095). Conference organized by Department of Chemical Engineering, SVNIT, Surat.

SARDAR VALLABHBHAI NATIONAL INSTITUTE OF TECHNOLOGY

Surat 395007 – India

Certificate of Participation

This is to certify that *Rahul Waghmare* having ASREEM ID ASIN0095 has presented an Oral Presentation titled *"Review on Agrophotovoltaic systems with a premise on thermal management of photovoltaic modules therein"* co-authored by *Ravindra Jilte, Sandeep Joshi and Pranjali Tete* for Session 9A at Virtual International Conference on **Advances in Sustainable Research for Energy and Environmental Management** (ASREEM-2021) organized by Department of Chemical Engineering, Sardar Vallabhbhai National Institute of Technology, Surat (India) on August 06 – 08, 2021.

Dr. Arvind K. Mungray | Dr. V. N. Lad | Dr. Alka A. Mungray | Dr. M. Chakroborty | Dr. Jogender Singh

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International Conference-2

- Rahul Waghmare, Ravindra Jilte, Sandeep Joshi, 'Performance analysis of Agrophotovoltaic systems with Solanum lycopersicum crops' Advances in Mechanical Engineering (ICAME-2022) June 23-25, 2022 (Paper ID: ICAME-2022-301). Conference organized by Department of Mechanical Engineering, COEP, Pune.

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2nd International Conference & Exposition on

Advances in Mechanical Engineering

(ICAME-2022)

Certificate of Participation

This is to certify that

Rahul Waghmare

of

LPU, Punjab

has presented the paper titled

Performance analysis of agrophotovoltaic systems with solanum lycopersicum crops

by

Rahul Waghmare, Dr. Ravindra Jilte, Dr. Sandeep Joshi

*in the 2nd **International Conference & Exposition onAdvances in Mechanical Engineering**, organized by the **Department of Mechanical Engineering**, **College of Engineering Pune** during **June 23-25, 2022**.*

Prof. Suhas S. Mohite
Organizing Secretary
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Prof. M. R. Nandgaonkar
Convener
ICAME-2022

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Annexures-01

Instruments Calibration Certificates:

RPK / FT / 13

Calibration Certificate

Certificate No. CC-2475

ULR No.	CC247521000004048F	ELECTROTECHNICAL CALIBRATION	
Certificate No.	Calibration Date	Next Calibration Date (As suggested by customer)	Page
RPK/NABL/3989/01/21-22	25.08.2021	25.08.2022	1 of 2

Name & Address of Customer
M/s. Shri Ramdeobaba College of Engineering and Management,
Nagpur 440013

Customer Reference

Work order no. : --
Date : --
Date of Receipt : 21.08.2021
Physical condition on Receipt : Satisfactory
Location of Calibration : Lab/~~Site~~

Description & Identification of Unit Under Calibration (UUC) :

Name of UUC	Sr.No	Range	L. C	Make
12 CH .DIGITAL TEMPERATURE INDICATOR (WITH SENSOR)	DTI-3012	0 to 1000 °C	1 °C	CREATIVE

Reference Equipment used for Calibration :

Equipment	Sr. No.	Traceable to	Certificate No.	Valid Upto
Universal Calibrator	21080786	CC-2294	NI/2108/070/001	22.08.2022

Note: Measurements are metro logically traceable through NABL Traceability certificate of Master Equipment used.

Calibration Procedure & Ref. Documents : RPK/CM – ET/01 & EURAMET Cg-11

Environmental Condition Temperature : 30.4 °C Humidity : 70 % RH

Observation Table: -

CHANNEL NO:- 1 INPUT TYPE: K

SR. NO.	VALUE ON UUC (°C)	VALUE ON STANDARD (°C)	DEVIATION (°C)	* UOM (°C)
1.	100	100.2	-0.2	± 1.40°C
2.	200	200.1	-0.1	
3.	400	400.2	-0.2	
4.	600	600.3	-0.3	
5.	800	800.5	-0.5	
6.	1000	1000.5	-0.5	

Deviation = Value on UUC – Value on Standard
UUC = Unit Under Calibration
Uncertainty of Measurement at coverage factor $k = 2$ at 95.45% of Confidence Level.
Note: The certificate is issued subject to the condition stated overleaf.
Remark :- The Value on UUC / Standard Mentioned in observation Table are average of 5 reading.

Calibrated By
S. R. Bhowate
Tech. Asst.
Place : Nagpur
Issue Date : 25.08.2021

R.P. KHEDKAR CALIBRATION & TESTING CENTRE NAGPUR

Approved By
D. B. Bhalerao
Deputy Manager

-----END OF CERTIFICATE-----

R. P. KHEDKAR CALIBRATION & TESTING CENTRE
85, Azad Hind Nagar, (Trimurti Nagar) Jaitala Road, Nagpur- 440 022.
Ph. : 0712-2227318, 9822289333, E-mail : rpkhedkarlab@gmail.com

EVERON ENERGY SYSTEMS PVT LTD			
TEST REPORT			
MODEL NO : EV-DSL- 01		SR.NO:- 689	Date : 17-9-21
VOLTAGE CALIBRATION REPORT			
SL.NO	TEST VOLTAGE	READING BY EUT	ERROR/REMARKS
1	300.0	300.0	0 OK
2	249.7	249.8	.1 OK
3	203	203	0 OK
4	180.0	180.0	0 OK
5	150.4	150.4	0 OK
CURRENT CALIBRATION REPORT			
SL.NO.	TEST CURRENT	READING BY EUT	ERROR/REMARKS
1	11.4	11.4	0 OK
2	8.0	8.0	0 OK
3	5.0	4.9	.1 OK
4	3.0	2.9	.1 OK
5		1.0	.9 OK
# Standard Accuracy is +/-1% or FSD +/-1 Digit for Voltage and Current.			
Prepared by:-		Approved by:-	
Ramesh		N. Singh	

ANNEXURE-2

UNCERTAINTY ANALYSIS

In the experimentations, any measured quantity in most of the cases deviates from its true value. The numerous errors in performing experimentation cause such variation in the measured quantity. So, the important task is to represent the uncertainty that is the probability that an error may occur in experimentation. Further to estimate the uncertainty involves into the derived quantities of experimentation.

Henceforth, the experimental data to be globally acceptable, the range of the uncertainty involved in the derived quantity of experimentation should be presented. The popular methodology for the determination of uncertainty in the experimental data is suggested by Kline and McClintock, 1953 is used in the present work. The error distribution is assumed to be normal in nature and uncertainty for each variable is defined as;

$$C = a \pm b, \ (20 \text{ to } 1) \qquad \text{(A1)}$$

The above equation describes that the variable ‘C’, has the best value of ‘a’ and the odds are 20 to 1 that the actual value will be in the range of ‘±b’ for the best estimate.

If the response X, is dependent on number of independent fundamental quantities as y_i, distributed normally then the relationship between the interval of uncertainty for the variable u_i, and the uncertainty interval for the response u_X which gives the same odds for each of the variables and for the response, X, is

$$u_X = \left[\left\{ \frac{\partial X}{\partial y_1} u_1 \right\}^2 + \left\{ \frac{\partial X}{\partial y_2} u_2 \right\}^2 + \dots\dots\dots\dots + \left\{ \frac{\partial X}{\partial y_n} u_n \right\}^2 \right]^{\frac{1}{2}} \qquad \text{(A2)}$$

Where, the response X= X (y_1, y_2……….y_n)

In present experimentation, the uncertainty intervals values are presented in Table A-3.2. Before the start of the actual experimentation, the vital check on the possible experimental error is to be carried out and this help is proper selection of the equipments for experiments. The use of the hypothetical experimental data wherever required is made initially for error analysis so as to identify the crucial equipments for experimentation. The analysis performed with the experimental data is represented below. Table A3.3 indicates the final results of error analysis. Table A 3.1 indicates the necessary data to demonstrate the procedure for the uncertainty analysis.

Table A 3.1: Values of the measured parameters

S. No.	Measured Parameters	Symbol	Value
1	Length of the solar cell in PV module	L_{pv}	1976 mm
2	Width of the solar cell in PV module	W_{pv}	991 mm
3	Radiation Intensity	I_g	661.2 W/m^2
4	Temperature of PV module	T_{pv}	43.7^{o}C
5	Current generated by PV module	I	5.3A
6	Voltage of PV module	V	103.4 V
7	Power produced by PV module	P	550.8 W
8	Atmospheric Temperature	Ta	32.5 ^{o}C

(The average values of measured parameters for one month period are considered)

Table A 3.2: Uncertainty interval of various measurements.

Sr. No.	Measurement Entity	Instrument used	Uncertainty (odds 20 to 1)
1	Radiation Intensity	Pyranometer, Model –KippZonen/PM-10 Class-1	± 1.5%
2	Temperature of PV module	Thermocouples Creative, Thermal indicator: DTI-306	± 1.40^{o}C
3	Ambient Temperature	Psychrometer	± 0.1%
4	Current generated by PV module	Energy Meter Everon EV-DSL-01	± 1%
5	Voltage of PV module	Energy Meter Everon EV-DSL-01	± 1%
6	Power produced by PV module	Energy Meter Everon EV-DSL-01	± 1%
7	Units generated	Energy Meter Everon EV-DSL-01	± 1%

1. Maximum power generated by the module

$$P = V \times I$$

$$\delta P = \left[\left(\frac{\delta P}{\delta V} \times \delta V\right)^2 + \left(\frac{\delta P}{\delta I} \times \delta I\right)^2\right]^{0.5}$$

$$\delta P = \left[(V \times \delta I)^2 + (I \times \delta V)^2\right]^{0.5}$$

$$\frac{\delta P}{P} = \left[\left(\frac{V \times \delta I}{V \times I}\right)^2 + \left(\frac{I \times \delta V}{V \times I}\right)^2\right]^{0.5}$$

$$\frac{\delta P}{P} = \left[\left(\frac{\delta V}{I}\right)^2 + \left(\frac{\delta I}{V}\right)^2\right]^{0.5} = 0.00472$$

2. Electrical efficiency of the system

$$\eta ele = \frac{P}{(Ig \times Apv)}$$

$$\delta \eta ele = \left[\left(\frac{\delta \eta ele}{\delta P} \times \delta P\right)^2 + \left(\frac{\delta ele}{\delta Ig} \times \delta Ig\right)^2 + \left(\frac{\delta ele}{\delta Apv} \times \delta Apv\right)^2\right]^{0.5}$$

$$\frac{\delta \eta ele}{\eta ele} = \left[\left(\frac{\delta P}{P}\right)^2 + \left(\frac{\delta Ig}{Ig}\right)^2 + \left(\frac{\delta Apv}{Apv}\right)^2\right]^{0.5} = 0.01029$$

Table A3.3: Calculated uncertainties in the parameters.

S. No.	Description	Uncertainty	Odds 20 in 1
1	Maximum power generated by the module	± 0.47 %	Odds 20 in 1
2	Electrical Efficiency of the system	± 1.029%	Odds 20 in 1