

Shade Tolerant Crops Plantation on Farmland under Solar PV Panel



By

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Declaration

I hereby declare that the work contained in this thesis has not been previously submitted to meet requirements for an award at this or any other higher education institution. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is cited.

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Dedication

I want to dedicate this thesis to the Almighty Allah, who is the source of life and strength of knowledge and wisdom, for his guidance, power of the mind, and protection, and for giving me a healthy life to carry out this study.

This research is the fruit of countless and arduous sacrifices, which is heartily and proudly dedicated to the people who serve as an inspiration. This study is wholeheartedly dedicated to my beloved father, Jahedul Alam Chowdhury and my mother, Rokeya Begum, who have been my sources of inspiration and strength throughout this research. This thesis is also dedicated to my paternal grandmother, late Mrs. Shahjahan Begum, my elder sister, late Jannatul Mawa Sonia, my younger uncle, late Mohammad Arshad, my maternal grandfather, late Mr. Raja Miya, my maternal grandmother, late Asia Khatun. From parents, relatives and guardians to classmates and circle of friends, whom extended their help in the midst of problems while doing this work. Thanks for making me see this adventure through to the end.

I would also like to dedicate this research to the Institute of Energy Technology (IET), Chittagong University of Engineering and Technology (CUET).

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Status: Considered with Minor Correction.

Approval by the Supervisor

This is to certify that *Raihan Chowdhury* has carried out this work under my supervision, and that he has fulfilled relevant Academic Ordinance of the Chittagong University of Engineering and Technology, so that he is qualified to submit the following thesis in application for the degree of MASTER of SCIENCE in Energy Technology.

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Abstract

Agro-photovoltaic (APV) technology addresses the challenges of land-use competition by enabling simultaneous solar power generation and food production, thus mitigating potential economic, ecological, political, and social conflicts in Bangladesh's future energy landscape. This study investigates the growth and yield of shade-tolerant crops, including tomato, brinjal, green chili, lettuce, aloe vera, cucumber, snake-gourd and rose flowers, under shaded and non-shaded conditions. Key plant growth parameters such as height, number of leaves, flowers, fruits, and fruit weight are measured to evaluate crop performance in the APV system. The Land Equivalent Ratio (LER) is utilized to compare the efficiency of food and energy production in APV systems against traditional monoculture farming, identifying optimal crops for APV integration. Energy generation from a stand-alone APV (SAPV) system is measured and simulated using PVsyst software to optimize system performance and maximize power output. Electrical shading analysis is conducted to improve the synergy between crop growth and energy production. Results indicate that brinjal, lettuce, aloe vera, cucumber, and rose flowers exhibit yield advantages in the APV system, while green chili and snake gourd show disadvantages, and tomato demonstrates no significant difference. The SAPV system achieves an average yearly performance ratio of 75.4% and a solar fraction (FR) of 0.914, consistently meeting energy demands with an average daily energy production of 1.157 kWh. This study highlights the feasibility of APV systems as a sustainable model for integrated food and energy production in Bangladesh, demonstrating their potential to enhance land-use efficiency and contribute to the nation's energy and agricultural resilience.

বিমূর্ত

অ্যাগ্রো-ফটোভোল্টাইক (এপিভি) প্রযুক্তি ভূমি ব্যবহারের প্রতিযোগিতার চ্যালেঞ্জ মোকাবিলা করে একসঙ্গে সৌরশক্তি উৎপাদন এবং খাদ্য উৎপাদন সক্ষম করে। এটি বাংলাদেশের ভবিষ্যৎ জ্বালানি প্রেক্ষাপটে সম্ভাব্য অর্থনৈতিক, পরিবেশগত, রাজনৈতিক এবং সামাজিক সংঘাত হ্রাস করতে সহায়তা করে। এই গবেষণায় ছায়া-সহনশীল ফসল, যেমন—টমেটো, বেগুন, কাঁচামরিচ, লেটুস, অ্যালোভেরা, শসা, চিচিঙ্গা এবং গোলাপ ফুলের বৃদ্ধি ও ফলনের উপর ছায়াযুক্ত এবং অছায়াযুক্ত অবস্থার প্রভাব বিশ্লেষণ করা হয়েছে। গবেষণায় ফসলের উচ্চতা, পাতা, ফুল, ফল এবং ফলের ওজনসহ প্রধান বৃদ্ধি পরিমাপক গুণাবলী পরিমাপ করে এপিভি ব্যবস্থায় ফসলের কার্যকারিতা মূল্যায়ন করা হয়েছে। খাদ্য এবং জ্বালানি উৎপাদনের দক্ষতা তুলনা করতে ল্যান্ড ইকুইভ্যালেন্ট রেশিও (এলইআর) ব্যবহার করা হয়েছে, যা ঐতিহ্যবাহী একক চাষের সঙ্গে এপিভি পদ্ধতির কার্যকারিতা তুলনা করে এবং এপিভি ব্যবস্থায় অন্তর্ভুক্তির জন্য উপযুক্ত ফসল নির্ধারণ করে। স্ট্যান্ড-অ্যালোন এপিভি (এসএপিভি) সিস্টেম থেকে জ্বালানি উৎপাদন পরিমাপ করা হয়েছে এবং PVsyst সফটওয়্যারের মাধ্যমে সেটি সিমুলেট করা হয়েছে, যাতে সিস্টেমের কর্মদক্ষতা সর্বাধিক করা যায় এবং সর্বোচ্চ বিদ্যুৎ উৎপাদন নিশ্চিত হয়। ফসলের বৃদ্ধি এবং শক্তি উৎপাদনের মধ্যে সমন্বয় বৃদ্ধি করতে বৈদ্যুতিক ছায়া বিশ্লেষণ পরিচালিত হয়েছে। ফলাফল অনুযায়ী, এপিভি ব্যবস্থায় বেগুন, লেটুস, অ্যালোভেরা, শসা এবং গোলাপ ফুলের ফলনে ইতিবাচক প্রভাব দেখা গেছে, যেখানে কাঁচামরিচ এবং চিচিঙ্গার ফলনে নেতিবাচক প্রভাব লক্ষ্য করা গেছে এবং টমেটোর ক্ষেত্রে উল্লেখযোগ্য কোনো পার্থক্য পাওয়া যায়নি। জ্বালানি উৎপাদনের ক্ষেত্রে, এসএপিভি সিস্টেম গড় বার্ষিক কর্মক্ষমতার অনুপাত (পারফরম্যান্স রেশিও) ৭৫.৪% এবং সৌর ভগ্নাংশ (এফআর) ০.৯১৪ অর্জন করেছে, যা দৈনিক গড় ১.১৫৭ কিলোওয়াট-ঘণ্টা শক্তি উৎপাদন করে ধারাবাহিকভাবে জ্বালানি চাহিদা পূরণ করতে সক্ষম। এই গবেষণায় বাংলাদেশের জন্য খাদ্য ও জ্বালানির সমন্বিত উৎপাদনের একটি টেকসই মডেল হিসেবে এপিভি ব্যবস্থার সম্ভাব্যতা তুলে ধরা হয়েছে। এটি ভূমি ব্যবহারের দক্ষতা বৃদ্ধি এবং দেশের জ্বালানি ও কৃষি খাতের স্থিতিশীলতা নিশ্চিত করতে গুরুত্বপূর্ণ ভূমিকা রাখতে পারে।

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Nomenclature

Acronyms and Abbreviations

ACS712	Hall Effect-Based Linear Current Sensor it can measure both DC and AC.
AH	Ampere Hour
APV	Agro-Photovoltaics Technology
APV-RESOLA	An APV project is located in Heggelbach, Sigmaringen, Germany.
COP25	United Nations Framework Convention on Climate Change.
EME building	Electrical and Mechanical Engineering Building
GHG	Green House Gas
I-V characteristics	Current Vs Voltage Characteristics
LER	Land Equivalent Ratio
NPV	Net present value
PV	Photovoltaics
P-V characteristics	Power Vs Voltage Characteristics
PV-GM	Ground Mounted Photovoltaics
PVsyst	A solar simulation software tool.
RE	Renewable Energy
ROI	Return on investment
STAND-ALONE	Stand-Alone Agro-PV System
AGRO-PV	
SDG	Sustainable Development Goal
USA	United states of America
VDR	Voltage Divider Rule

Symbols	
<i>Yield of plants_{APV}</i>	Crops yield under agro-photovoltaics System
<i>Yield of plants_{no PV}</i>	Crops yield without agro-photovoltaics System
<i>Electricity Yield_{APV}</i>	Electrical Power Generation under agro-photovoltaics System
<i>Electricity Yield_{only PV}</i>	Electrical Power Generation without agro-photovoltaics System
I_{ph}	Photocurrent in Amperes
I_d	Diode current in Amperes
I_0	Saturation current in Amperes
$PR = \frac{Y_f}{Y_r}$	Performance ratio is the ratio of the PV system's actual yield (Y_f) to its reference yield (Y_r).

Chapter 1: Introduction

This chapter provides a general overview of PV power generation and agricultural activities concepts and their prospects in section 1.1. Section 1.2 describes the importance of an Agro-Photovoltaic System. Section 1.3 represents the basic description of Land Equivalent Ratio (LER). Basic concept of Standalone PV (Stand-alone Agro-PV) System is introduced in section 1.4. In section 1.5 describes Shade Tolerant Crops for APV system. Section 1.6 demonstrate the advantage of agro-photovoltaics system. Then, discuss the research hypothesis formulation of the thesis in section 1.7. Specific research aims, purposes, and objectives are reported in Section 1.8. Section 1.9 relates to the significance and scope of this research and provides definitions of the terms used. Then, discuss the organization of the remaining chapters of the thesis in section 1.10. Finally, section 1.11 includes the summary and concluding remarks of Chapter 1.

1.1 BACKGROUND

Agro-photovoltaics (APV), also known as agri-photovoltaics or agrivoltaics, is an innovative and integrative approach that combines agricultural production with solar energy generation on the same land area. This concept, (Goetzberger and Zastrow, 1982) first introduced the idea of agrivoltaics in 1981 by demonstrating that there might be enough sunshine beneath positioned photovoltaic modules to support the growth of specific crops., thus addressing the dual needs of food and energy production. Given the increasing global demand for sustainable energy solutions alongside the need to preserve agricultural land, APV offers a promising solution that aligns with global sustainability and food security goals.

In an APV system, solar panels are strategically placed above crops at certain heights and angles to allow for sunlight to reach the plants below. By

balancing shading and light requirements, APV systems create a microclimate that can potentially improve crop yields, reduce water consumption, and generate renewable energy. Research shows that certain crops, especially those that are shade-tolerant, can thrive in APV environments as the partial shading from solar panels helps reduce water loss and stress due to excessive heat. This multifunctional use of land becomes particularly advantageous in regions where competition for arable land is high or where climate conditions necessitate crop protection from intense sunlight.

Recent advancements in APV technology, including the development of bifacial solar panels and adjustable mounting systems, have further enhanced the feasibility and efficiency of APV systems. The adaptability of APV setups to different crop types, climatic conditions, and geographic areas opens up substantial opportunities for its implementation worldwide, particularly in regions with high solar irradiance and arable land shortages. Additionally, APV systems contribute to local economies by providing an additional source of income for farmers through energy sales while promoting decentralized energy production, which is essential for energy resilience in rural areas.

The growing interest in agro-photovoltaics reflects a broader trend in sustainable agricultural practices and renewable energy integration. This dual-use technology has the potential to mitigate some of the most pressing environmental challenges, such as greenhouse gas emissions, deforestation, and water scarcity. However, successful APV implementation requires addressing several challenges, including optimizing crop selection, panel configuration, and regulatory frameworks that support its development. This thesis aims to explore these critical factors and assess the viability of APV systems in specific agricultural settings, with a focus on their technical, economic, and environmental impacts. Through a detailed analysis, this research will contribute to a deeper understanding of the potential of agro-photovoltaics as a sustainable solution for the future of energy and food security of Bangladesh.

1.2 DIFFERENT AGRO-PHOTOVOLTAIC TECHNOLOGY

The growing global population and industrial energy consumption are driving up world-wide energy demand. The European Union (EU) stipulated that by 2020, 20% of energy must come from renewable sources (Renewable Energy Directive, 2009/28/EC). At the same time, the threat of global warming is changing tactics for producing energy. Green energy production is not without its detractors, particularly when it impedes on land use, as the fuel vs. food debate illustrates. This is true even if it is closely linked to sustainable development. Solar photovoltaics (PV) is the renewable energy source with the quickest rate of technological advancement. PV energy requires less land than other renewable energy sources, but its landscape integration should be planned to minimize unfavorable changes to land use and promote community acceptance. There are a lot of possible drawbacks when PV power generation and agricultural activities are combined. Agro-photovoltaic practices can be carried out in different ways depending on the activities carried out by the population in a given area which shown in Figure 1.1. Different agro-photovoltaics technology such as crop grown in between solar rows, grazing in between or underneath the solar panels, Vegetation's in between or underneath the solar panel, Panel reinforced with tracker bases, elevated reinforced panels, Greenhouse solar are introduced are introduced in Figure 1.1.

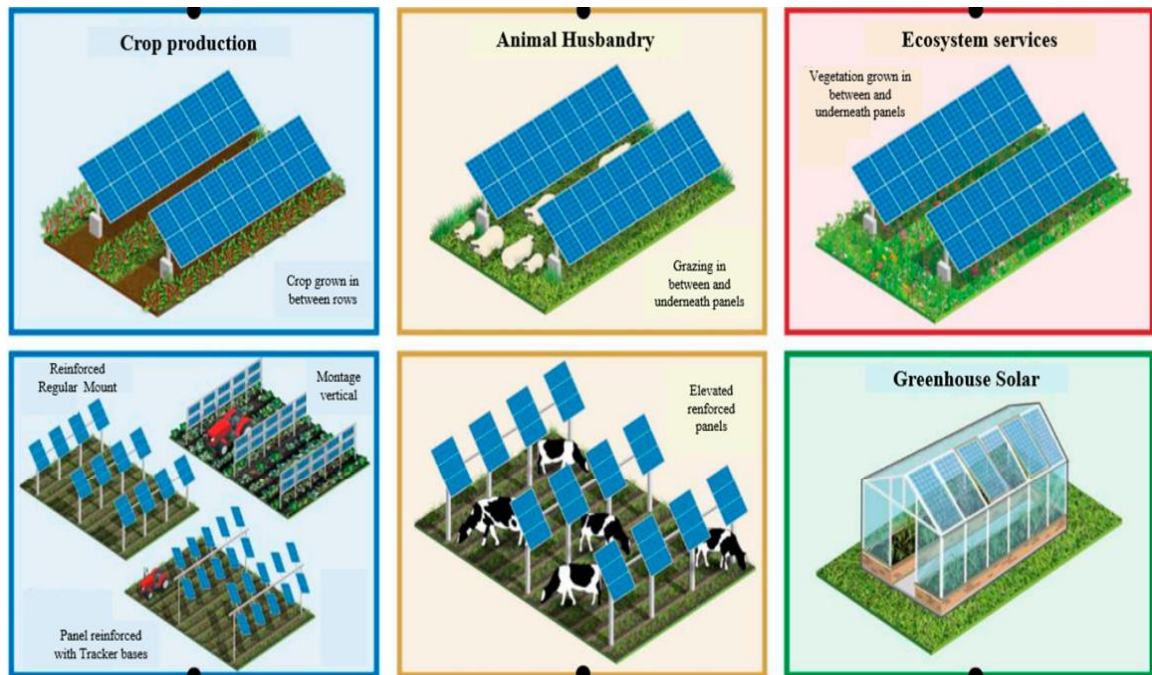


Fig. 1.1: Different agro-photovoltaics technology.

Agro-photovoltaic applications represent the combination of energy production with (i) agricultural production in the field or (ii) agricultural production in greenhouses or livestock rearing, or (iii) provision of ecosystem services through vegetation management or (iv) different agricultural practices combined.

1.3 AGRO-PV ALIGNMENT WITH SDG GOALS AND 4IR

1.3.1 Alignment with Sustainable Development Goals (SDGs):

- **SDG 2: Zero Hunger**
 - Promotes sustainable food production by improving crop yield and water efficiency.
- **SDG 7: Affordable and Clean Energy**
 - Provides renewable energy solutions through solar photovoltaics, reducing reliance on fossil fuels.
- **SDG 12: Responsible Consumption and Production**
 - Maximizes land productivity by integrating dual-use systems for food and energy.
- **SDG 13: Climate Action**

- Reduces greenhouse gas emissions and mitigates climate change impacts through clean energy generation.
- **SDG 15: Life on Land**
 - Prevents land degradation by promoting efficient land use practices.

1.3.2 APV in the Fourth Industrial Rev. (4IR):

- Smart Technologies
 - Integration of IoT sensors for monitoring solar output, soil health, and crop growth.
- AI and Machine Learning
 - Predicts energy production, optimizes water use, and determines the best crop-solar configurations.
- Automation and Robotics
 - Use of drones and robots for precision farming under APV systems.
- Data-Driven Decision Making
 - Real-time data collection and analysis for improved agricultural and energy productivity.
- Sustainable Innovations
 - APV serves as a model of green innovation, driving industrial transformation towards sustainability.

1.4 DETAILS OF AGRO-PHOTOVOLTAIC SYSTEM

By 2050, the global population is projected to reach 9.8 billion [1], necessitating a 70% increase in food production to meet the demand [2]. Simultaneously, climate change, driven by human activity and population growth, poses a significant threat to global food and water security. Average global temperatures are now 0.95–1.2 °C higher than in the late 19th century, with severe and erratic weather patterns contributing to worldwide catastrophes [3]. These changes place immense pressure on the agricultural sector [4], calling for innovative solutions that balance food security and climate mitigation.

Renewable energy sources, particularly agro-photovoltaics (APV), offer a promising approach to addressing these challenges. APV technology aims to maximize land use by integrating crop cultivation with solar energy generation. Unutilized solar light that passes through or around photovoltaic (PV) modules can benefit crops grown beneath or between rows of panels. Studies have demonstrated various financial and ecological benefits of APV systems, including improved land-use efficiency, greater crop yields, and reduced water usage. For example, the Fraunhofer Institute for Solar Energy Systems ISE reported land-use efficiencies of 160% in 2017 and 186% in 2018 at its Heggelbach test site in Germany [5]. In arid and semi-arid regions, APV systems mitigate the effects of intense solar radiation, heat, and dryness by shading crops, thus reducing environmental stress and boosting yields [6]. Additionally, crops prone to damage from UV exposure, hail, wind, or rain can thrive under the protective shelter of PV panels [7]. Water conservation is another key benefit; APV systems have been shown to save up to 20% of irrigation water and reduce evapotranspiration by 14% to 29% [8].

The integration of APV systems also supports energy production, which can supplement farmers' incomes. Improved convective cooling under APV setups enhances PV module efficiency, with studies indicating temperature reductions of up to 10 °C, leading to minimized efficiency losses [9], [10]. Given that PV panel efficiency decreases by approximately 0.6% per °C above standard test conditions, such cooling effects are particularly significant [11].

Bangladesh has also begun exploring the potential of APV technology. A notable example is a 3.77 MW APV project in Pabna, which utilizes 12.5 acres of land as part of the Soudia-Agro Solar PV Power Plant [12]. The project, costing approximately \$7 million USD, is expected to supply electricity to the national grid for 20 years at a fixed rate of \$0.1074/kWh. This initiative exemplifies the practical implementation of APV systems in addressing the dual challenges of

energy and food security. Table 1.1 and Table: 1.2 lists low-yield crops suitable for APV systems and overview of existing literature on the effect of shading on different crops. These insights lay the groundwork for further exploration of APV's potential to achieve sustainable agricultural and energy solutions.

Table 1.1: List of crops that have low yield under APV.

Type of Crop	Condition	APV yield (Kg/m^2)	Conventional Yield (Kg/m^2)
Bok Choy [13]	Under PV panel	0.10	1.15
Corn [14]	Under PV panel (high density)	3.23	3.35
Lettuce [15]	Greenhouse	2.18	2.03
Lettuce [16]	Under PV panel	2.65	4.50
Kiwi [17]	Under PV panel (low density)	1.66	1.71
Winter cabbage [18]	Under PV panel	0.32	0.35

Table 1.2: Overview of existing literature on the effect of shading on different crops.

Crop	Shade effect	Effect on yield	RSR^b (%)	Type/Time of shade application	Study site
Tomato [19]	+	Increased fruit yield under moderate shading conditions	25/50/75	Unknown	Indonesia, Egypt
Sunflower [20]	-/+	Decreased seed set and number in all shading treatments	80	At various period	Buenos Aires, Argentina
Potato [21]	-/+	Decreased tuber yield and number	50	Non-uniform shading; at various periods	Kalpitiya, Sri Lanka
Rice [22]	-	Reduced grain yield through shading during reproductive and ripening stages	22/52/77	At various growth stages	Joydebpur, Bangladesh
Wheat [23]	-/+	Decreased grain yield and grain size	55	Non-uniform shading; starting at flowering	Gembloux, Belgium
Sweet pepper [24]	+	Decreased tuber yield and number	12/26/47	At various period	Negev desert, Israel

Agro-photovoltaics (APV), despite its potential benefits, presents challenges that need to be addressed for successful implementation. While APV systems can shield crops from excessive sunlight, reduced light availability may adversely affect crop yields [25]. For example, studies by Fraunhofer ISE have reported yield reductions for crops such as winter wheat, potatoes, celery, and grass/clover in certain years [26]. Similar reductions have been observed in tomatoes, lettuce, and rice [27], [28].

Nevertheless, APV holds immense promise when applied appropriately. Converting less than 1% of the world's croplands to APV systems could offset global energy consumption, demonstrating its potential as a sustainable energy solution [29]. Research conducted by the Fraunhofer Institute for Solar Energy Systems (ISE) during 2017-2018 showcased the effectiveness of APV systems in potato production, achieving a land-use efficiency increase of approximately 186% compared to mono-cropping practices [30].

The integration of APV systems within agricultural fields does pose operational challenges. The presence of photovoltaic (PV) panels can impose spatial constraints, limiting the maneuverability and size of agricultural machinery and necessitating the use of precision or modified equipment [31]. Additionally, regular maintenance practices, including cleaning and inspecting PV panels, ensuring structural integrity, and managing electrical components, are essential for sustained energy production [32]. Effective vegetation management and synchronization with agricultural practices are also vital to minimize disruptions and maximize the efficiency of both farming and energy generation [33].

Despite these challenges, APV systems demonstrate adaptability, as no significant obstacles have been reported for pesticide application or irrigation due to the presence of PV panels. Moreover, advancements in design and technology provide pathways to mitigate existing challenges, as summarized in Table 1.3. By addressing these operational and technical barriers, APV systems can be optimized for broader adoption and long-term sustainability.

Table 1.3: Scope to mitigate challenges from APV by improving design and technology.

Challenges	Solution by improved design	Solution by improved technology
Maximize electricity generation	Tilt angle close to latitude Avoid shading from the other modules and crops.	Semi-transparent type PV, LSC can be helpful.
Maximize crop production	Need knowledge of shade tolerant and intolerant crops. Depending on the crops PV can be selected for vertical or tilted orientation	If the crops are shade intolerant, the choice should be vertical bifacial PV. In shade-tolerant crops, suitable semi-transparent PV is needed.
Public acceptance	Lower reflection and more improved design are essential.	Finding appropriate crops for the location and based on the light requirement choosing the PV.

Separate Land Use on 1 Hectare Cropland: 100% Potatoes or 100% Solar Electricity



1 Hectare (100% potatoes)



1 Hectare (100% Solar Electricity)

Combined Land use on 1 Hectare cropland: 186% Land use efficiency



1 Hectare (103% potatoes + 83% Solar Electricity)

Fig. 1.2: Through the combined land use, the land use efficiency with the APV system is 186% [30].

Agro-photovoltaic (APV) technology offers a promising solution to the challenges of sustainable land use by integrating food and energy production. This study investigates the use of APV solar energy in conjunction with horticultural crops such as brinjal, tomato, green chili, aloe vera, lettuce, cucumber, snake gourd, and rose flowers under both shaded and non-shaded

conditions. The system demonstrates that APV can enhance crop resilience to climate change, with crops benefiting from reduced drought stress when grown under the shade of solar panels. The Land Equivalent Ratio (LER) is employed to compare the combined benefits of food and energy production in an APV system to those of conventional monoculture farming. This analysis determines the potential advantages of renewable energy generation through APV technology. Additionally, the study evaluates the commercial viability of shade-tolerant crops by analysing gardening plantations with and without shade. The proposed method includes system loss predictions and economic analyses of a stand-alone APV system. By shading the ground, APV technology significantly reduces evapotranspiration and increases water use efficiency. Ultimately, the APV system enables the production of renewable energy on farmland without compromising soil productivity or agricultural output.

1.5 CONCEPT DESIGN OF AGRO-PHOTOVOLTAICS TECHNOLOGY

The strategic arrangement and positioning of solar panels over crops optimizes the country's food and energy production. For the system to operate at its best, the solar panels should be oriented toward south-east. As shown in Figure 1.3, the basic design for installing solar panels in an APV includes plantings, structure, orientation, location, site evaluation, and stand-alone agro-photovoltaics system components. In order to achieve optimal power generation, the spacing between the panels must both moderate the micro-climate and provide enough light for photosynthesis. This lowers the panel's temperature by one to twenty degrees Celsius below the surrounding air. Compared to power generated using fossil fuels, this electricity generation will assist cut the CO₂ emissions from the same land use in half.

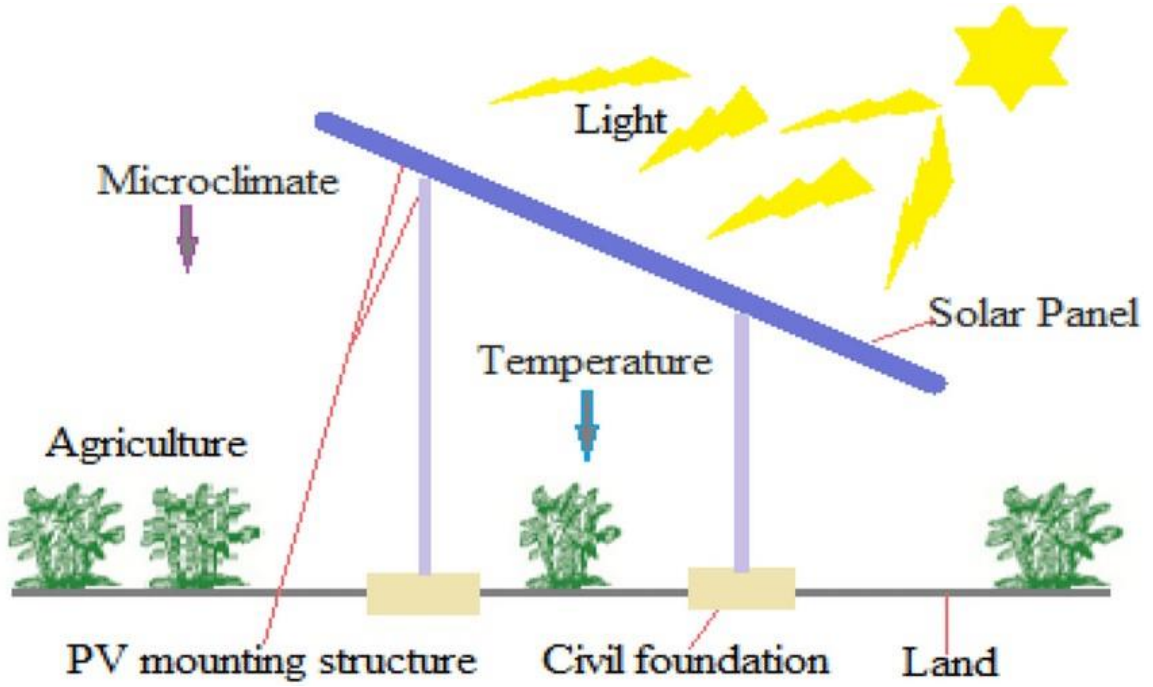


Fig. 1.3: Concept design of agro-photovoltaic system.

1.6 LAND EQUIVALENT RATIO (LER) OF THE APV SYSTEM

The Land Equivalent Ratio (LER) is a measuring parameter used in agriculture to assess the efficiency of intercropping systems compared to sole cropping [34.] It quantifies the relative advantage of growing multiple crops together in the same space compared to growing them separately [104].

The LER is calculated based on the principle that different crops have different resource requirements and growth patterns. When crops are grown together, they may complement each other in terms of resource use, capturing sunlight, nutrients, and water more efficiently [105].

The formula for calculating the Land Equivalent Ratio is:

$$LER = \frac{Yield\ of\ plants_{APV}}{Yield\ of\ plants_{no\ PV}} + \frac{Electricity\ Yield_{APV}}{Electricity\ Yield_{Only\ PV}} \quad (1.1)$$

Where $Yield\ of\ plants_{APV}$ indicates Grain yield in APV scenario (kg/m^2), $Yield\ of\ plants_{no\ PV}$ indicates Grain yield in full light scenario (kg/m^2), $Electricity\ Yield_{APV}$ indicates Electricity yield in APV scenario from PV

(kwh/m^2), *Electricity Yield_{only PV}* Indicates Electricity yield in a ground-mounted scenario from PV (kwh/m^2).

However, decision-making can be possible using following prospective output.

If $LER > 1$, the APV system has Yield Advantages.

If $LER = 1$, the APV system has no Yield Advantages.

If $LER < 1$, the APV system has Yield disadvantages.

Intercropping can have several benefits, such as improved resource utilization, reduced pest and plant disease, and increased overall productivity. The LER is one of the ways to quantify and compare the advantages of intercropping systems.

1.6.1 Electricity Yield Only PV System perspective to Bangladesh

Bangladesh's annual average solar insolation ranges between 4 and 6.5 kWh/m²/day, positioning the country as an ideal location for solar PV systems. **Based on this solar potential, a 300-watt PV system could generate approximately 1.2 to 2 kWh of electricity per day under optimal conditions,** taking into account system efficiency losses due to factors such as temperature effects, wiring inefficiencies, and inverter losses [117], [118].

Research published in the Journal of Renewable and Sustainable Energy and various reports highlight that the daily energy output of such systems varies across different regions in Bangladesh. Variability in solar irradiation levels, particularly between the northern and southern parts of the country, results in slight regional differences in energy production potential [118].

1.6.2 The electrical yield of an APV system is generally lower than that of a standalone photovoltaic (PV) system due to several factors:

- **Shading Effects:** In APV systems, partial shading is often unavoidable due to the placement of PV panels elevated to accommodate agricultural activities. This shading reduces the intensity of sunlight received by the panels, thus lowering their energy output. In real-life scenarios, **climbing**

plants can exacerbate this shading effect by covering parts of the panels, further minimizing electrical power production [119], [120].

- **Orientation and Design Limitations:** APV systems are designed with a balance between solar energy generation and agricultural productivity. Panels are often spaced or tilted to optimize land use, which can result in less direct sunlight exposure compared to standalone systems optimized for maximum solar capture [120].
- **Microclimatic Effects:** While vegetation beneath the panels can help create cooler microclimates, which may benefit crops, this can also lead to localized temperature variations that slightly affect PV performance [120].
- **Maintenance Challenges:** The presence of vegetation, including climbing plants, increases maintenance requirements for cleaning and clearing panels to mitigate shading and ensure maximum energy output [120].

While standalone PV systems are optimized purely for energy generation and achieve higher yields, APV systems prioritize multifunctional land use, offering the dual benefits of renewable energy production and sustainable agriculture. Despite their lower electrical yield, APV systems enhance overall land-use efficiency and provide resilience against climate impacts [119], [120].

1.7 STANDALONE PHOTOVOLTAICS SYSTEM

A standalone photovoltaic (PV) system, often referred to as "standalone PV," operates independently of a centralized power distribution network and does not connect to the electrical grid. This system relies on photovoltaic technology, where solar cells convert sunlight into electricity. Such systems are particularly valuable in remote locations where grid access is costly or impractical, offering a sustainable and reliable power source for diverse applications such as telecommunications, off-grid housing, and rural electrification [35].

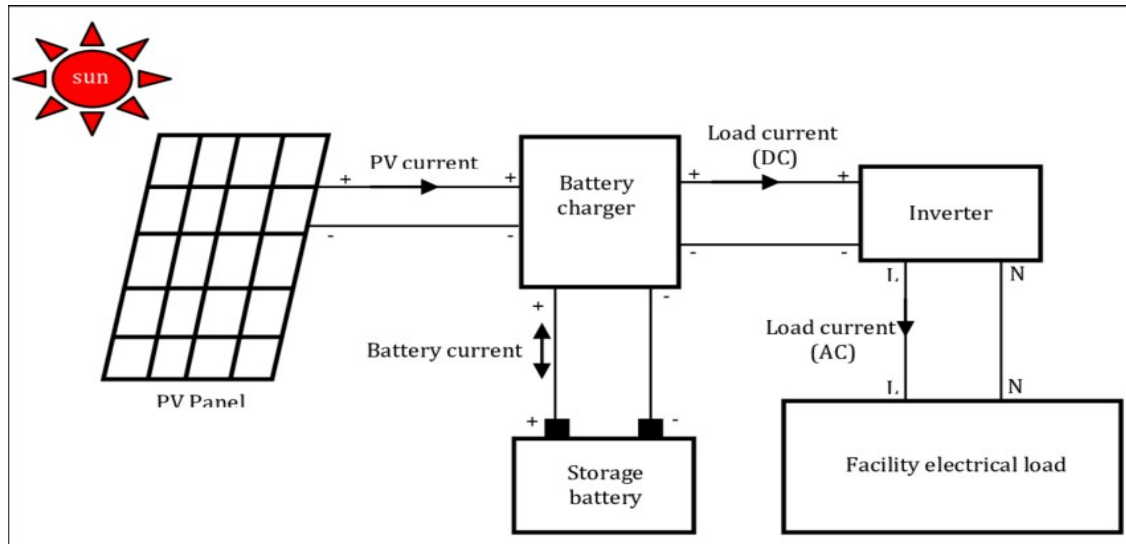


Fig. 1.4: Illustrates the configuration of a standalone photovoltaic system, showcasing its essential components

All the components of stand-alone photovoltaic system's essential parts include:

1. **Solar Panels (PV Modules):** Solar panels are the core components of the system. They capture sunlight and convert it into direct current (DC) electricity through the photovoltaic effect [36].
2. **Charge Controller:** The charge controller plays a critical role in protecting the batteries by regulating the charging and discharging process. It prevents overcharging and deep discharging, which could otherwise damage the batteries and reduce their lifespan.
3. **Battery Storage:** Excess electricity generated by the solar panels during sunlight hours is stored in batteries. This stored energy ensures a continuous power supply during periods of low or no sunlight, enhancing the system's reliability.
4. **Inverter:** The solar inverter converts the variable DC output from the solar panels into utility-frequency alternating current (AC), enabling compatibility with standard electrical appliances or local off-grid networks.

5. **Electrical Loads:** Electrical loads refer to the devices and appliances that consume the electricity generated by the system, such as lighting, fans, or communication equipment.

Standalone PV systems provide energy independence and can be customized to meet specific power requirements. They are increasingly used in off-grid settings, contributing to rural development and environmental sustainability. By reducing reliance on fossil fuels, these systems also help mitigate greenhouse gas emissions [37].

1.8 SHADE TOLERANT CROPS FOR AGRO-PHOTOVOLTAICS SYSTEM

In agro-photovoltaic (APV) systems, shade-tolerant crops are crucial for maintaining productivity under solar panels, which partially block sunlight. The selection of crops that can thrive under reduced light levels is essential to maximizing both crop yield and energy production, as these crops can better adapt to the shade cast by solar arrays. By carefully choosing shade-tolerant varieties, APV systems can sustainably integrate food and energy production on the same land, contributing to improved land-use efficiency and resource sustainability [33], [38].

Table 1.4: List of Crops for Different Light Conditions

Light condition	Plant for agro-photovoltaic system	
Shade Intolerant Plant	Cabbage, corn, cucumber, pumpkin, rice, tomato, turnip, and watermelon	
Shade Tolerant	Full shade Light	Alfalfa, arugula, Asian greens, broccoli, cassava, chard, collard greens, hog peanuts, kale, kohlrabi, lettuce, mustard greens, parsley, scallions, sorrel, spinach, sweet potatoes, taro, and yam
	Moderate Light	Beans, carrots, cauliflower, coriander, green chili, and onions
	Low Light	Mushroom

Types of Shade-Tolerant Crops:

1. Leafy Greens

- **Lettuce:** Certain lettuce varieties are shade-tolerant and yield well even under reduced sunlight
- **Arugula:** Known for partial shade tolerance, arugula is a popular leafy green in APV setups.

2. Herbs

- **Parsley:** Grows effectively in partial shade, commonly cultivated for culinary uses.
- **Chives:** Adaptable to areas with lower sunlight, chives add versatility to shaded gardens.

3. Root Vegetables

- **Radishes:** Fast-growing and able to tolerate some shade, making them suitable for shaded plots.
- **Carrots:** While preferring full sun, carrots can still grow in shaded conditions, though yield may be impacted.

4. Berries

- **Blueberries:** Can adapt to partial shade, though full sun is generally optimal for berry production.
- **Currants:** Some currant varieties thrive in shaded areas, adding diversity to APV systems [31].

5. Shade-Tolerant Grains

- **Quinoa:** Versatile in light requirements, quinoa can grow in partial shade, suitable for APV setups.

6. Perennial Plants

- **Hostas:** Though primarily ornamental, hostas are highly shade-tolerant and can support soil conservation in APV fields.

7. Culinary Mushrooms

- **Shiitake Mushrooms:** Adapt well to shaded conditions, providing a valuable food source for shaded APV areas.

8. Cool-Season Vegetables

- **Broccoli:** A cool-season crop that performs well in partial shade.
- **Cauliflower:** Similar to broccoli, cauliflower can tolerate low-light conditions and maintain reasonable yield [39].

When implementing a shade-tolerant APV system, understanding the specific light conditions is crucial. Adjusting panel orientation, using reflective materials, and optimizing planting patterns can help improve the available light for shade-tolerant crops. Additionally, proper soil preparation, nutrient management, and crop selection contribute to successful crop yield in APV environments.

1.9 ADVANTAGES OF AGRO-PHOTOVOLTAICS TECHNOLOGY

Agro-photovoltaic (APV) technology offers multiple benefits by combining solar power generation with agricultural production on the same land. This integration allows for efficient resource use and a range of socio-economic and environmental advantages, enhancing both renewable energy production and agricultural yield.

- **Increased Land Productivity:** APV systems have the potential to boost land productivity by up to 70–80% as they enable the simultaneous production of crops and electricity on the same plot. This dual-use approach allows land owners to diversify income streams through leasing, electricity sales, and enhanced agricultural output, thus benefiting the broader agricultural sector [31], [33].
- **Water Use Efficiency:** Solar panels in APV setups often require periodic cleaning to remove dust and optimize performance. By positioning crops underneath the panels, runoff water used for panel cleaning can also irrigate plants below, thereby improving water-use efficiency and maximizing the utility of each water cycle [31], [33].
- **Improved Soil Health and Reduced Dust:** Vegetation grown under photovoltaic panels helps protect the soil surface from erosion by

stabilizing the top layer, which enhances soil health over time. This coverage also reduces dust generation, contributing to better air quality and creating a more favorable environment for the plants [38].

- **Lower Local Ambient Temperature:** Shaded agricultural land beneath solar panels retains moisture and exhibits cooler temperatures than open land. This cooler microclimate can improve photovoltaic efficiency, as lower ambient temperatures reduce thermal stress on the panels and increase power output. Additionally, the shade mitigates excessive evapotranspiration, reducing water needs for crops [40]
- **Social and Economic Benefits:** APV technology can contribute to rural community development by providing economic opportunities and infrastructure improvements, potentially slowing migration from rural to urban areas. By promoting local jobs, including roles that empower women in agricultural operations, APV initiatives encourage community stability and economic growth
- **Human Health and Safety:** For agricultural workers who face the risk of heatstroke and skin cancer from prolonged exposure to direct sunlight, APV structures provide essential shade, thereby reducing these health risks and enhancing the overall safety and comfort of the working environment.
- **Livestock Production Potential:** APV can also accommodate livestock grazing, especially after crop harvests. Once the primary crops are cut and collected, the land is available for grazing, thus supporting dual-use of farmland for crop and livestock production [31].
- **Support for EV Charging:** APV installations in rural areas offer a promising solution for electric vehicle (EV) charging infrastructure. Since remote locations often lack charging stations, the electricity generated by APV systems can serve as a source for EV charging stations, alleviating range anxiety for long-distance EV travel [39].

- **Rural Off-Grid and Grid Electrification:** Many agricultural areas are situated in rural regions that lack reliable access to electricity. APV systems present an opportunity for off-grid electrification, supporting United Nations sustainable development goals for affordable energy access in underserved communities. APV-generated electricity can power homes, schools, and medical facilities in remote areas, enhancing rural quality of life [33].

1.10 RESEARCH HYPOTHESIS FORMULATION

Based on the discussion in the earlier sections, the following hypotheses are formulated to address the challenges associated with sustainable land usage for food and energy production:

1. **Primary Hypothesis:** Agro-photovoltaic (APV) technology can effectively resolve the dual challenges of sustainable land usage by simultaneously supporting food production and energy generation.
2. **Sub-Hypotheses:**
 - Shade-tolerant plants are essential for optimizing agricultural productivity in APV systems.
 - Gardening plantations with and without shade will show significant differences in growth performance, highlighting the impact of solar panel shading.
 - Daily energy generation can be accurately evaluated through practical measurements and simulations, providing insights into system efficiency.
 - Electrical shading analysis is crucial to minimizing power loss, ensuring optimal energy output, and efficiently feeding surplus energy into the grid.

- Calculating the Land Equivalent Ratio (LER) will identify the most advantageous plants for integration into the APV system, maximizing land-use efficiency.

1.11 RESEARCH AIMS, PURPOSES AND OBJECTIVES

Research Aim:

To investigate the integration of agro-photovoltaic (APV) systems with horticultural crop production, focusing on shade-tolerant crops, energy generation, and land-use efficiency to enhance sustainable food and energy production in the context of Bangladesh.

Research Purposes:

1. To explore the potential of shade-tolerant horticultural crops for sustainable agriculture in APV systems.
2. To evaluate the technical performance of a stand-alone APV model for simultaneous crop production and energy generation.
3. To assess the economic and practical feasibility of APV systems for rural electrification and agricultural development.

Research Objectives:

- To analyze gardening plantations with and without solar panel shade to identify differences in crop growth and productivity.
- To determine suitable shade-tolerant crops for APV systems in Bangladesh's climatic and agricultural context and evaluate the land equivalent ratio (LER) to maximize land-use efficiency.
- To evaluate the performance ratio and daily energy output of the system
- To analyze and quantify PV system losses throughout the year

1.12 SIGNIFICANCE AND SCOPE

Significance:

This research is significant as it addresses the growing challenges of land-use competition for energy and food production in Bangladesh, offering a sustainable

solution through agro-photovoltaic (APV) technology. By integrating solar power generation with horticultural crop cultivation, the study aims to:

1. Provide a benchmark solution for sustainable land use, balancing food and energy production.
2. Enhance economic and ecological sustainability by identifying commercially viable shade-tolerant crops.
3. Maximize energy generation while optimizing agricultural productivity.
4. Promote efficient resource utilization, and increased overall land productivity.

Scope:

The research focuses on:

1. Investigating the performance of horticultural crops, such as tomatoes, brinjal, lettuce, and cucumber, snake-gourd, green chili, rose flower, alovera under shaded and non-shaded conditions.
2. Evaluating daily solar power generation in an APV system through practical measurements and simulation using PVsyst software.
3. Conducting shading analysis to minimize energy loss and ensure optimal power and crop yields.
4. Assessing the land equivalent ratio (LER) and economic feasibility of APV systems for potential implementation in Bangladesh.
5. Providing actionable insights into the integration of APV technology as a sustainable approach to address future energy and food security challenges.

1.13 THESIS STRUCTURE

Including the above introductory chapter, this dissertation contains the following five chapters (Chapter 2 to Chapter 6). The remaining chapters of the thesis are organized in the following arrangement with a short chapter description.

Outline of Chapter 2

This chapter provides historical background on sustainable and clean RE and their prospects in Section 2.1. Section 2.2 describes the Overview of the agro-PV technology. Specifically, Fundamental Technical Parameters of APV System. Section 2.3 highlights the exiting APV project all over the world. Section 2.4 represents the Agricultural land use scenario all over the world. Grapes production under different PV modules in APV project are reported in section 2.5. Then, demonstrates the different PV modules use in APV project. Then, I discuss the Characteristics of Solar Cell in section 2.7. Finally, section 2.8 includes the Carbon footprint in APV system. Finally, section 2.9 includes the summary and concluding remarks of Chapter 2.

Outline of Chapter 3

This chapter outlines the research design employed to achieve the aims and objectives defined in Section 1.10 of Chapter 1. It provides an in-depth explanation of the Crops Plantation model under Solar Photovoltaic Panels, exploring its potential benefits and practical implications. Section 3.1 presents an analysis of gardening plantation models, comparing those utilizing shaded areas with those grown in unshaded conditions, while discussing their prospects. Section 3.2 focuses on the implemented Agrivoltaic (APV) system design, detailing its structural and operational factors. In Section 3.3, the Land Equivalent Ratio (LER) is introduced to evaluate the benefits of stand-alone agrivoltaics in optimizing land use efficiency. Section 3.4 provides an overview of the system's load calculation and the corresponding load profile curve, which are crucial for understanding the energy demands of the proposed design. Section 3.5 delves into a detailed electrical shading analysis, assessing its impact on both photovoltaic performance and crop productivity. Finally, Section 3.6 summarizes the key findings and offers concluding remarks for this chapter.

Outline of Chapter 4

This chapter provides the overall evaluation of results and their performance of Stand-alone APV system. Section 4.1 describes the Gardening plantation using Shade and without shade. However, total 8 crops are studied such as Tomato, Brinjal, Green chili, Lettuce, Cucumber, Aloe vera, Snake-gourd, Rose flower. All those are analysed in terms of plant height, Number of leaves, number of flowers and fruits, size of fruits and weight of the shade and non-shaded crops are introduced. Then, discuss Performance Analysis of stand-alone APV model using PVSyst Software are discussed in Section 4.2. Electrical Shading Analysis are discussed in Section 4.3. Section 4.4 demonstrate the LER analysis of the proposed APV system. Finally, Section 4.5 includes the summary and concluding remarks of Chapter 4.

Outline of Chapter 5

This chapter presents a comprehensive analysis of system losses and the economic feasibility of a stand-alone Agrivoltaic (APV) system. Section 5.1 focuses on evaluating the system losses associated with the APV system, identifying key contributors to performance degradation. Finally, Section 5.2 provides a summary of the chapter's findings and concludes with key remarks.

Outline of Chapter 6

So far, this chapter provides a comprehensive summary of the research and simulation results presented throughout the thesis. It consolidates the key aspects of the study, including the introduction, methodology, results, and discussion from the previous chapters, while offering a concise conclusion of the overall research conducted. The chapter is structured to provide a clear overview of the study's key findings, limitations, and implications, along with recommendations for future research. Section 6.1 presents a summary of this research without detailed interpretation. The significant findings are tied together, and a few possible implication issues are in Sections 6.2. Recommendation for further study is explained in section 6.3.

1.14 SUMMARY AND CONCLUSIONS

The introductory chapter underscores the significance and rationale behind the proposed stand-alone agro-photovoltaics (APV) system, combining food and energy harvesting. It establishes the foundational understanding by exploring the concepts and prospects of photovoltaic (PV) power generation and agricultural activities. The importance of APV systems is highlighted, including detailed explanations of the Land Equivalent Ratio (LER), shade-tolerant crops, and standalone PV systems. The chapter effectively demonstrates the advantages of integrating APV systems, emphasizing their sustainability and dual-purpose functionality. Additionally, it presents the formulation of the research hypothesis, system design, and clearly outlines specific research aims, objectives, and purposes. Finally, it concludes with a summary of the chapter's contents and outlines the structure for the subsequent chapters.

2 Literature Review

The twenty-first century is currently in grave danger of global warming owing to the emission of carbon due to the production of energy from fossil fuels for the last two hundred years. Reliance on renewable energy (RE) alone can protect us from environmental pollution, climate change, and global warming. Renewable clean energy will balance our future for a living, securing energy reliability and the sustainable development of a country. This research will explore the agro-photovoltaic system where crops and electricity are produced and save the land. Future economic, ecological, political, and social conflicts could result from growing land use rivalry brought on by rising demand for solar energy output. Technology for agro-photovoltaic (APV) systems offers a solution to the problems associated with sustainable land use for the production of food and electricity. We have found that APV improves land use efficiency by first enabling the production of agricultural crops and secondarily producing solar PV power simultaneously within the same agricultural area, while optimally utilizing the synergistic technological and techno-economic effects of both production systems. Japan, France, Massachusetts (USA), South Korea, and China have all enacted policies that assist the deployment and spread of the APV industry since 2017.

This chapter provides historical background on sustainable and clean RE and their prospects in Section 2.1. Section 2.2 describes the Overview of the agro-PV technology. Specifically, Fundamental Technical Parameters of APV System. Section 2.3 highlights the exiting APV project all over the world. Section 2.4 represents the Agricultural land use scenario all over the world. Grapes production under different PV modules in APV project are reported in section 2.5. Then, demonstrates the different PV modules use in APV project. Then, I discuss the Characteristics of Solar Cell in section 2.7. Finally, section 2.8 includes the Carbon footprint in APV system. Finally, section 2.9 includes the summary and concluding remarks of Chapter 2.

2.1 RENEWABLE ENERGY AND SUSTAINABLE DEVELOPMENT

Renewable Energy (RE) is a unique, readily available energy derived from sun-oriented renewable resources that are naturally renewed on a human timeline, and it is usually associated with sustainable electricity. Sunlight (solar), hydro, wind, rain, ocean, tides, and geothermal waves are all examples of RE sources. Almost 100% of RE sources are created 24 hours a day, year-round, in a specific area, region, or nation to fulfill all energy requirements. Various RE's might be generated de-centrally to cover the local energy demand (electricity production, irrigation, heating, cooling, transportation) or imported from outside the region utilizing equipment and technology like electrical networks, hydrogen, or hot water. Also, various energy storage devices must be used to balance the energy source.

Almost 190 nations have pledged to provide dependable, affordable, and sustainable energy to all of their residents by 2030, according to the Sustainable Development Goal-7 (SDG-7). As a result, the SDG-7 has precise regulations for generating power from renewable energy, which was overwhelmingly adopted at the Paris Agreement-2015 (COP25) [41]. By 2030, practically every country will have significantly reduced electricity output from fossil fuels and will be focusing on renewable energy, according to the policy. As a result, global warming is expected to be limited to 1.5°C. However, according to the Glasgow Agreement-2021 (COP26), it is not as envisaged even if power is generated from renewable energy [41]. Many countries are still interested in using fossil fuels (coal) to generate power. As a result, a number of scientists anticipate that global warming will exceed 1.5°C by 2030, which is quite concerning. Power generation from coal has been adjusted from a “phase out” to a “phase down” strategy due to objections from some nations, notably China and India. Bangladesh announced the shutdown of around ten of its pre-planned coal-fired power stations during the COP26 meeting, which is likely to encourage other countries. Effective carbon

emission policies and actions are expected in the upcoming Egypt Agreement-2023 (COP27).

Aside from significant de-carbonization, many governments understand that switching to a 100% RE source might have enormous socioeconomic implications with more affordable and reliable energy, more economic growth, and many environmental and health benefits [42]. Pollution, security of energy, sustainability, and the effects of climate change are just a few of the significant challenges that the modern global economy faces [43]. According to some researchers, transitioning to a 100% renewable economy is the best way to find a long-term solution to these obstacles [44]. This decision was made due to the reality that renewables are a well-established, fast-growing technology with the potential to be carbon-free. This last characteristic makes them particularly well adapted to dealing with climate change, which is perhaps humanity's most serious problem [45]. Any RE transition will undoubtedly be aided in the medium term by judicious use of natural gas because it is known as the less-carbon deployable energy that may supplement intermittent renewables [46]. According to several research, Bangladesh's economy would become entirely renewable in the long run, which would take between 40 and 50 [47] years to complete a significant infrastructure restructuring and an internationally coordinated policy action. Governments have failed to embrace a concerted policy approach despite the urgent need for such a shift to avert disastrous climate change [48]. According to various renowned researchers [49], a realistic time for the start of a Bangladesh RE transition may be when all the source fossil fuel generation is depleted, which is estimated to occur between 2030 and 2050, with completion in the second part of this century.

Transitioning to 100% RE is critical to our better future because the environmental costs of burning fossil fuels and growing economic concern lead us to climate change's quickening effects, which are disadvantageous for human beings. In modern times, burning coal, oil, and gas-based fossils to generate

electrical power originate in around 69% of GHG releases [50]. According to a recent estimate, if global warming stays below 1.5°C to 2°C, 50% of the gas reserves, around 68% of oil stocks, and around 80% of current coal stocks must not be consumed before 2050 [51]. To avoid reaching irreversible tipping points, an immediate effort is necessary to shift to 100% RE. The fact of the matter is that a complete switch to renewable energy is no longer a daft idea, thanks to the rising availability of financial and legislative incentives that make switching to renewable energy sources more feasible. Various governments worldwide have already achieved their 100% RE objectives, and others are on their way to being completely fossil and nuclear-free civilizations. A bold goal of 100% RE is about more than just changing our whole energy source; it is also about a more comprehensive vision of a brighter future. Other advantages of transitioning to a fully RE-powered society include reduced water, air, and land pollution; security and resilience in the energy sector, sustainable economic growth, employment, health benefits, social and human development, and, because of its inherent decentralized nature, chances for more excellent democratic choice and citizen engagement. Effective policies and practices may be learned throughout the globe, and we are convinced that this will be critical in providing government decision-makers with a toolkit of instruments, tactics, and specific actions to achieve a 100% RE objective effectively.

In Bangladesh, the aim of a complete RE system is currently more achievable than ever. In recent years, RE technologies and technical innovation costs have decreased substantially. These advancements, along with mature market and regulatory frameworks and targeted innovations, enable fast-rising RE participation in various sectors such as the power industry, transportation [52], cooling, and heating sectors to fulfill national energy requirements [53]. Setting targets has also been a valuable strategy for enhancing deployment and directing policymakers and investors toward a common aim. To fulfill all end-use energy requirements, Bangladesh will strive for very high renewable percentages as

soon as feasible. Solar photovoltaic (PV) deployment is expected to rise significantly, building on current large concentrations of wind, biomass, and waste-to-energy, combined with a better RE economy to reduce overall electricity demand [54].

According to the findings of the analytical method, around 40% of Asian [55] and Pacific nations [56] and about 70% of European countries [57] might achieve 100% RE generation by 2050 [58]. Some towns in North America [59] and Canada [60] have already achieved the goal of using 100% RE. By 2030, African nations might produce roughly 25% of their energy [61]. For various reasons and scenarios, public authorities and community leaders have viewed RE production as a chance, not a duty. Residents in smart communities powered entirely by RE will ensure savings, generate various employment options, and have a higher standard of living. They are the cornerstone of a new economy and a future based on sustainable energy. As more nations strive for 100% sustainable energy, each one will undoubtedly confront a unique set of possibilities and difficulties. Access and affordability of land, regional weather concerns, and several socio-economic issues may be constraints in some areas. However, attaining 100% RE for smart cities is a difficult challenge.

Bangladesh is a small part of around 45 countries in Asia, which is the world's largest continent. Asia is home to about 80% of the world's total population [62]. According to Asian area sources [56], [57], [62], [63], Fig. 2.1 depicts the country-by-country total RE mix. The blue bars show the current RE percentage share of that country's overall energy output. The light-green circles represent each country's 2050 RE objective, which will range from 50–90% RE share. The RE share represents the power produced by various solar, wind, hydro, geothermal, biomass, and other emerging RE generating sources. As shown in Fig. 2.1, nearly half of the countries covered have a RE proportion of less than 20%. Almost half of the world's future intelligent cities are located in Asia. Even though Nepal

generates around 90% of its electricity from renewable sources (mainly hydro), the energy generated is insufficient to fulfill demand, and residents frequently experience power outages [62]. The 26th United Nations Climate Change Conference-2021 (COP26) is presently taking place in the SEC Centre in Glasgow, Scotland, where nearly 120 countries, including Bangladesh, expect to run totally on renewable energy by 2050. However, industrialized Asian regions, especially Southeast Asia and the Middle East, rely on coal, gas, and oil for electricity production [56], [63].

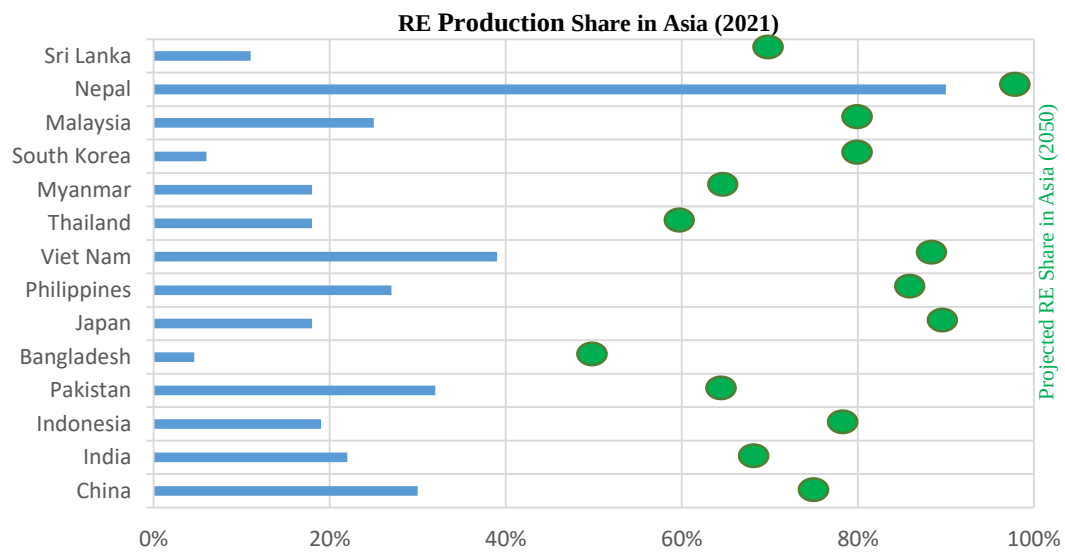


Fig. 2.1: Asian countries RE percentage share (blue bars) in 2021 and RE set targets (light-green circles) by 2050 [56], [57], [62], [53].

2.2 OVERVIEW OF THE AGRO-PHOTOVOLTAICS TECHNOLOGY

One of the biggest socio-economic concerns of our day is finding ways to replace fossil fuels with renewable energy sources so that we can meet the world's energy needs while also preventing climate change. In this context, agro-photovoltaic systems (APV) are described as mixing soil-grown crops with photovoltaic (PV) panels positioned several meters above the ground. Goetzberger and Zastrow first suggested the idea of agro-photovoltaics (APV) in 1982 as a way to alternative solar power installations to allow for more agricultural production in the same area.

Agro-photovoltaic systems (APV) are described as mixing soil-grown crops with photovoltaic (PV) panels positioned several meters above the ground. PV systems are crucial to reducing global warming and achieving climate change objectives. The PV structures are able to transform solar energy into electricity. Photovoltaic electricity must be stored so that it can be utilized during non-sunny hours. In addition to electrical energy, solar energy has numerous diverse applications, including water heating, space heating, solar pumps, and dryers [5, 6] etc. You can reach this goal either by using batteries or by connecting the power system to the grid. Domestic and small-and medium-sized businesses can profit greatly from roof-mounted systems that lower their peak loads. The performance ratio is an essential metric for assessing PV efficiency. It connects the real and theoretical outputs of solar energy, despite losses like inefficient inverters, cable losses, cells that do not match up well, and module temperature losses, among others. Solar yield, performance ratio, and system losses are crucial characteristics. Performance Ratio values can vary based on environmental conditions, mounting method, and electrical design. During days with high temperatures, using coolants that prevent solar PV cell modules from overheating can boost their performance.

They assumed that these systems would only need a third of the radiation that enters the area and that additional technological advancements may make them more suitable for use in crop cultivation. The use of agro-photovoltaic solar energy in conjunction with horticultural crops such brinjal, tomato, green chili, cucumber, snake-gourd, alo vera, lettuce and rose flowers will be investigated in this research. Average grain output may be more stable under agro-photovoltaic than under full light in rain-fed circumstances. This suggests that agro-photovoltaic systems could increase crop resilience to climate change. Crops may benefit from growing in the shade of agro-photovoltaic systems proportionally to drought stress. The Land Equivalent Ratio (LER) will be used to compare the electric energy produced by agro-photovoltaic farmed with foods to that

produced by a mixture of conventional ground growth crops in monoculture in order to determine the benefits of producing renewable energy using agro-photovoltaic. The Land Equivalent Ratio was greater with sun tracking panels than static panels, increased with panel density, and remained consistently greater than one. The agro-photovoltaic system is useful for producing renewable energy on a farm without impairing the production of the soil. Today, there are more than 2200 APV systems deployed throughout the world, with a total APV capacity of an approximately 2.8 GW [64]. Solar system related challenges are Political challenge; Market share and Mechanical structure support are the major concern in this regard. There are some drawbacks in this regard such as; Crop cultivation under agro-photovoltaic panels may result in decreasing crop production because sun radiation will be reduced there by around of one third. Agro-photovoltaic systems can boost land productivity by up to 70% by combining energy and agricultural production. If yield losses due to shading effects are reduced by the choice of suitable crops, calculations have shown that the implementation of this technical method can enhance farms' earnings by over 30% [66]. However, panel density rather than panel mobility has a greater impact on the amount of radiation available beneath the Agro-photovoltaic system array [66]. In order to maintain reasonable agriculture production, the density of the PV arrays must be lower than for typical ground-mounted PV installations. It is assumed that a row spacing of roughly 3 meter is sufficient to let enough amounts of sunlight to reach the crop canopy while still producing satisfactory energy yields.

2.2.1 Fundamental Technical Parameter of the APV System

Agro-photovoltaic systems are now the most economically viable method of energy generation on an international market. The main technical parameters of the stand-alone agro-photovoltaics technology are noted in Figure 2.2 and can be summarized as follows: The PV modules are elevated with a clearance height

of 5 meter so that the work of the agricultural machinery, in particular of the combined harvester, is not hindered by the APV power plant. The overall height of the installation reaches 7.8 m. Each individual unit has a width of 19 m, having been chosen to be many times the width of the machine most frequently used for this particular cropland. This ensures that as little area as possible is lost and reduces the additional work for the farmer to a minimum. Overall, the APV system takes up seven units in width, adding up to a total width of 133 m. The length of each unit is 13m and was also chosen by multiple of the farm's most common machines so that the farmer can process the field in both directions of the APV power plant in future. The power plant is two units long, resulting in a total length of 26 m. In order to ensure uniform crop growth, the APV installation must guarantee sufficient and homogeneous light distribution. This proposed model will simultaneously be cultivating crop plants and utilizing the energy of sunlight and controls exposure to sunlight during the plant's entire vegetative phase. Rising interest in the sun-based force age will increase land-use competition, which could lead to conflict on the economic and social facets. According to research, 30% of all energy used globally is used for farming [67]. More than 30 years ago, in 1982, Goetzberger and Zastrow introduced the idea of agro-photovoltaic [68].

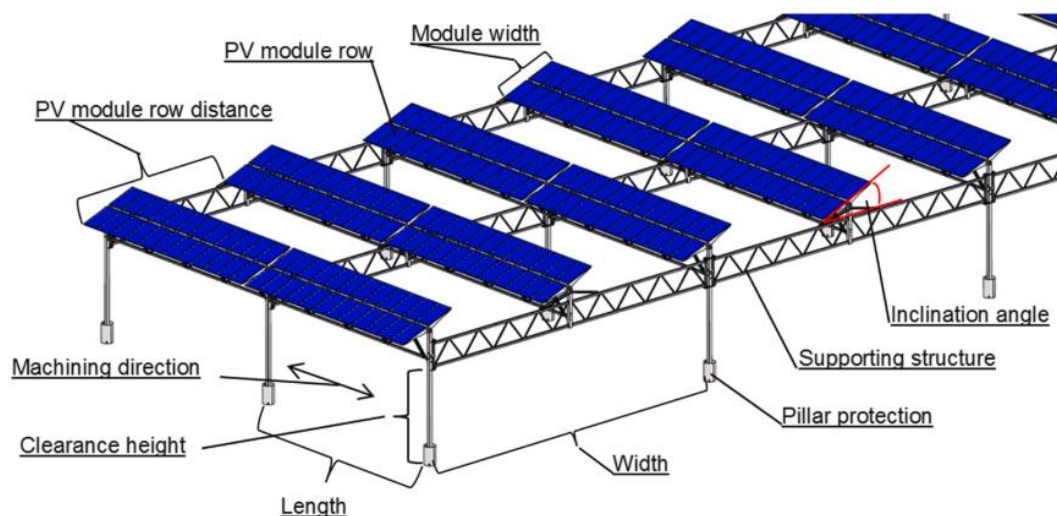


Fig. 2.2: Fundamental technical parameters of APV system technology.

As a result, the market for Photovoltaic system is seeing an increase in the use of agro-photovoltaic systems. Agro-photovoltaic systems can boost land production, as shown by numerous research [69]. When agro-photovoltaic technology is applied, the amount of land for energy production significantly lowers [70]. The land provides food, clean water, and a variety of other ecological resources, which is the foundation of human existence. Not every type of agricultural crop is appropriate, but plants with fewer roots and a higher net photosynthetic rate are the prime choices [71]. Agro-photovoltaic systems have been proven to boost energy production systems' value by 30% and enhance land productivity by 60–70% [72]. M. Guggenmos tested wheat and vegetables in southern Bavaria and had excellent results with his non-optimized PV plant [73]. Recently, a very thorough study that included a real experiment in the south of France was published [74]. The sensitivity of agricultural plants to shade at temperate latitudes is not well-understood [74]. Micro-climatological and soil moisture measurements were made in the Rabbit Hills Agro-photovoltaic solar arrays, which are on the Oregon State University campus, from May to August of 2015 as part of the experimental setting. The Oregon State University library system provides access to the field data used in this study [75]. They experimented with two different PV module densities in order to achieve a production mix that was equally balanced in terms of food and energy. The best circumstances for simultaneous crop production were discovered under less dense PV modules [77], even though PV yield rose with panel density [76]. To enable conventional agricultural equipment to pass below, the solar panels were raised to a 4-m clearance height. The APV systems' most promising potential might be anticipated in dry areas, whereas a number of synergistic effects may take place. Increased water savings from decreased evapotranspiration and the negative effects of excessive radiation may boost crop output, while economic viability is improved and rural electrification is made possible [78]. According to

research, APV may reduce crop losses in dry years and increase yield stability by reducing soil evaporation [79].

2.3 EXISTING APV PROJECT ALL OVER THE WORLD

In the past several years, several commercial and research APV facilities have been realized shown in Table 2.1 and Figure 2.4. Since 2004, a number of small-scale APV projects have been constructed in Japan which known as "solar sharing," comprise PV panels installed on 3-meter-high poles. They combine the generation of solar energy with the development of several local food crops, including peanuts, yams, eggplants, cucumbers, tomatoes, taros, and cabbages [81]. In recent years, a few APV projects have also been implemented in Europe. In addition, a number of research centers in France and Germany, three commercial APV projects, patent-protected as "Agro-photovoltaic," have been implemented in Northern Italy. Using mounted solar modules (4–5 m in height) and sun-tracking technology, the installed systems have capacities of up to 1500 kWp [81]. Another APV farm in Abruzzo employs 67 standalone solar trackers to create a total output of 800 kWp from crops such as tomatoes, watermelons, and wheat [88].

Table 2.1: Overview of Existing APV Facilities with Technical Specifications and Crops Cultivated Underneath [80].

SL No.	Location	Country	Electricity Yield [$KWha^{-1}$]	Capacity [KWp]	Solar Tracking System	Cultivated Crops
1	Monticeli D'Ongina	Italy	4,842,000	3230	Yes	Winter Wheat, Maize
2	Castelvetro	Italy	1,890,000	1294	Yes	Winter Wheat, Maize
3	Virgilo	Italy	3,325,000	2150	Yes	Winter Wheat, Maize
4	Abruzzo	Italy	Unknown	800	Yes	Pasture, Tomato, watermelon, wheat
5	Anhui Province	China	887,000	544	Yes	Unknown

6	Zhejiang province	China	40,000,000	30,000	Yes	Rice
7	Arizona	USA	Unknown	Unknown	No	Cabbage, tomato, Onion
8	Montpellier	France	Unknown	Unknown	Partly	Cucumber, durum wheat, French bean, lettuce
9	Heggelbach	Germany	244,401	194	No	Various cabbage varieties
10	Santiago de Chile	Chile	21,437	Unknown	No	Various cabbage varieties
11	Chiba prefecture	Japan	35,000	Unknown	No	Cabbage, Cucumber, eggplant, peanut, tomato, taro, yam
12	Soudia Agro Solar PV Power Plant Pabna	Bangladesh		3770	No	Vegetables



Fig. 2.3. APV application in different countries.

Figure 2.3 shows some pilot agro-photovoltaics application in different countries (Bangladesh, China, France, Italy, India, Germany, Saudi Arabia, Netherland, South-Korea) all over the world.

Figure 2.4 depicts some commercial and research APV facilities all over the world. Monticelli D'Ongina, Italy, Castelvetro, Italy, Virgilio, Italy, Campo D'eco, Abruzzo, Italy, Jinzhai Plant, Anhui, Changshan Plant, Zhejiang are patronized commercially with specific goal. On the other hand, Biosphere 2, Arizona, USA, Montpellier, France, Heggelbach, Germany, Santiago de Chile, Chile, Chiba prefecture, Japan project are built with a view to research purpose. The first prototype APV research facility in the south of France was separated into two sub-systems with varying PV panel densities to study the impact on sunlight distribution and energy generation [90]. In a follow-up study, conducted a field trial with four lettuce cultivars to validate the results of simulations [91].

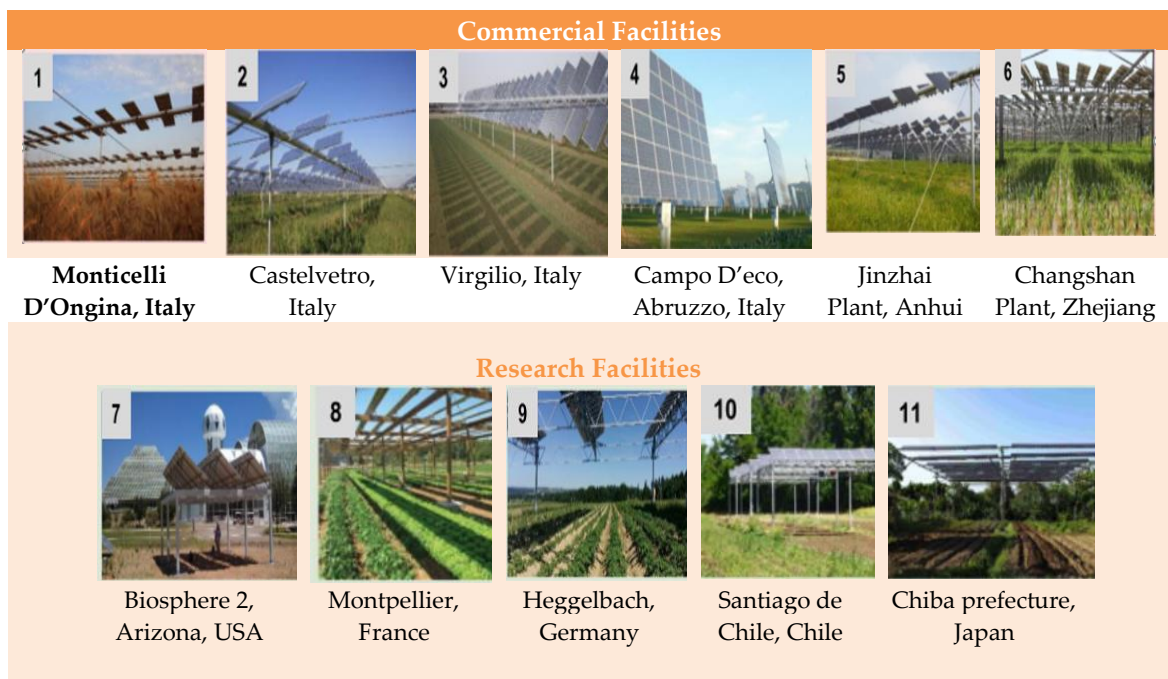


Fig. 2.4: Several commercial and research APV facilities in the world [81].

They examined the effects of APV systems on plant growth, morphology, yield, and microclimatic conditions. Further species, including cucumber, French beans, and durum wheat, were planted to evaluate their usefulness in crop rotations. In their studies, the scientists utilized an APV system with solar panels

that were permanently attached. Proposed that solar-tracking technology may be used to achieve additional agricultural and PV performance improvements [91]. As indicated before, this methodology has been applied in a second study that examines the usage of solar trackers and the potential benefits for energy and agricultural production compared to systems with stationary PV panels [92].

2.3.1 APV RESOLA Project in Heggelbach, Germany

During the last two years, the collaborative project "Agro-photovoltaics – Resource Efficient Land Use (APV-RESOLA)" has evaluated the dual use of land for the production of solar power and agriculture. On a five-meter-tall structure situated on a third of an acre of agricultural ground near Lake Constance in Germany, solar modules with a total power output of 194 kilowatts. Figure 2.5 shows the APV-RESOLA project which located in Heggelbach, Sigmaringen, Germany. Its application in agricultural production is presently under investigation (the APV-RESOLA project was supported by the German Federal Ministry of Education and Research) [93]. Also Figure 2.6 shows the Potato harvesting under APV panels in 2017 [93].



Fig. 2.5: Growing Potatoes Beneath an APV Facility (APV RESOLA)

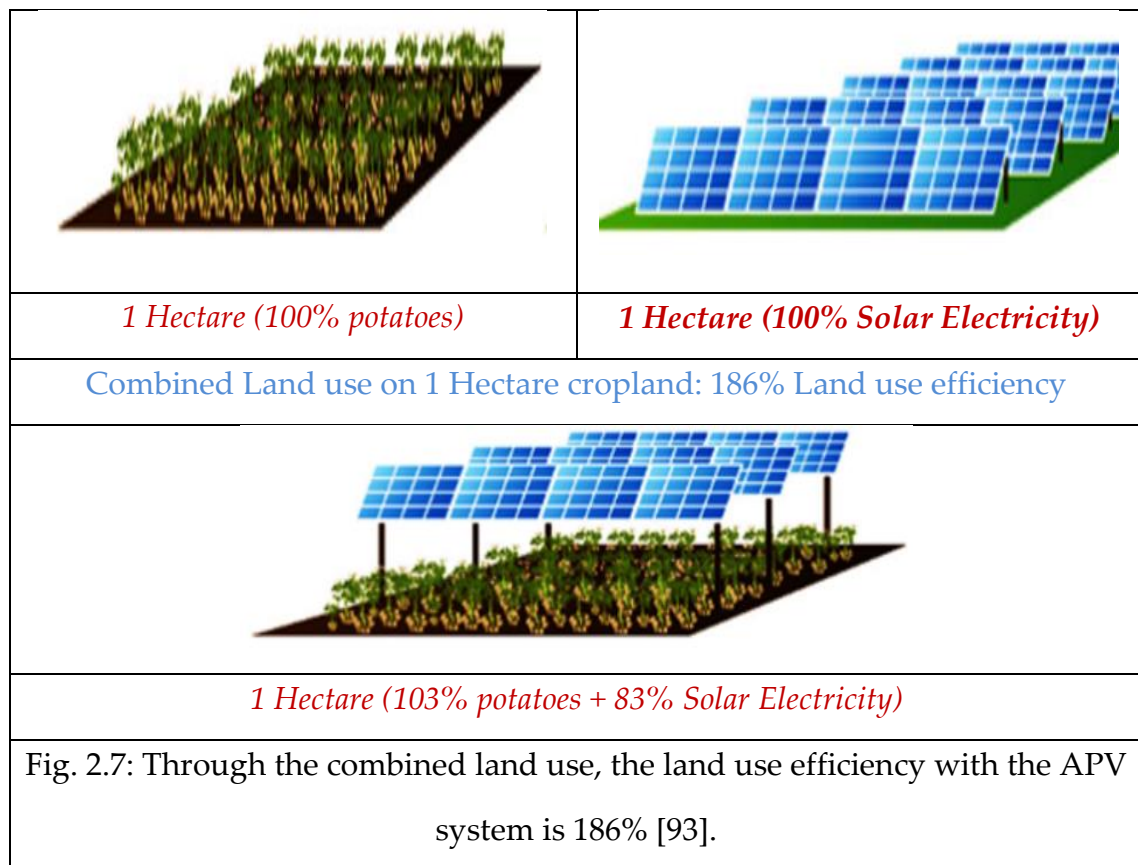


Fig. 2.6: Potato harvesting under APV panels in 2017 (Source: farm community Heggelbach) [93].

2.3.2 APV Project in Fraunhofer Institute for Solar Energy Systems ISE

In 2017 findings demonstrated a land usage efficiency of 160 percent, as validated by the project partnership led by the Fraunhofer Institute for Solar Energy Systems ISE. In 2018, a biodynamic farming community of Heggelbach, harvested their second successful crop from their agro-photovoltaic system. Winter wheat, potatoes, clover, and celery were the four crops cultivated. In 2018, the yields of three of the four crops cultivated using an agro-photovoltaic system exceeded the benchmark yield. Celery crop yields benefited the most from the method, increasing by 13% over the baseline. Winter wheat increased by 3 percent, while clover decreased by 8 percent. "Based on the 2018 potato production, the agro-photovoltaic system increased land use efficiency to 186% per hectare," said Fraunhofer ISE's Stephan Schindele which mentioned Figure 2.7 [93].

Separate Land Use on 1 Hectare Cropland: 100% Potatoes or 100% Solar Electricity



2.3.3 LER Calculation in APV RESOLA Project

APV RESOLA project, Considering the yields of both electricity and harvestable products, LERs ranged from 1.56 to 1.70 in 2017 and from 1.67 to 1.87 in indicates in Figure 2.8 [99]. Overall, these productivity increases clearly indicate an extraordinarily high level when compared to other mixed systems, such as agroforestry. Additionally, the stark differences between the two years showed how much weather-related factors, such as temperature, moisture, and sunshine affect.

LER <1 indicates that combined crop and energy production is less Productive than separate production. In contrast, LER >1 indicates increased productivity in the APV system as compared to mono production. LER equal to 1 indicates that no yield advantageous.

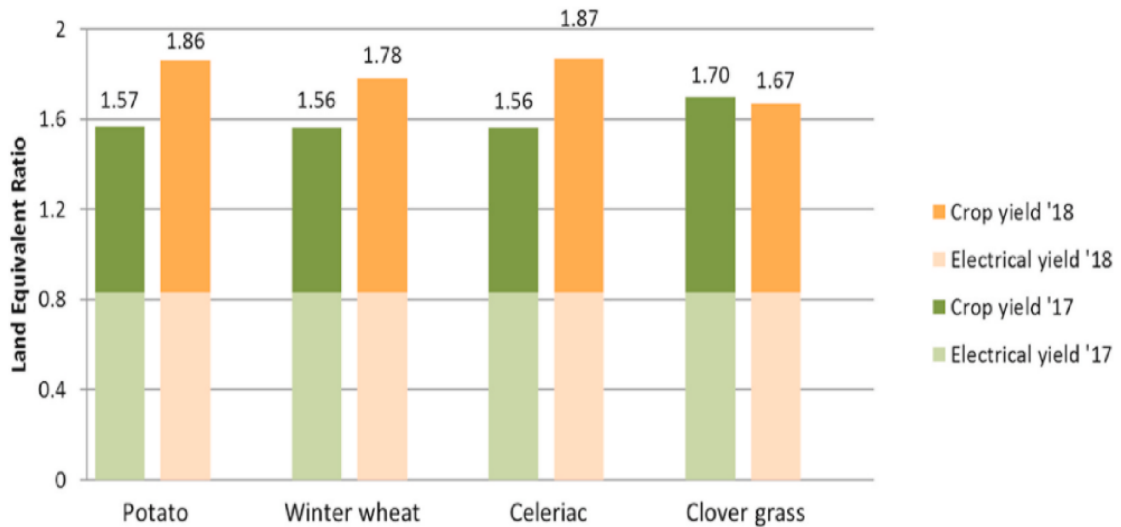


Fig. 2.8: LERs of four crops measured during two consecutive years under varying weather conditions [99].

However, In Figure 2.9 Shows an example of intercropping system and its Land Equivalent Ratio (LER) calculation. Here, Grain and Fruit crops are planted 5T and 15T using 0.8 ha and 0.6 ha respectfully. On the other hand, using 1 ha grain and fruit intercropped 4T/ha,9T/ha respectfully. After the LER calculation 1.4 its indicated that yield advantageous.

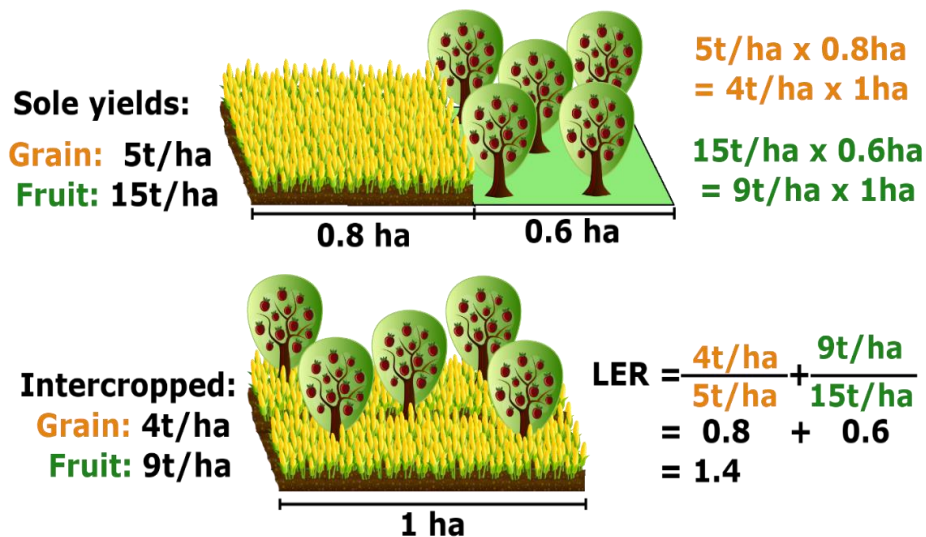


Fig. 2.9: Shows an example of intercropping system and its LER calculation.

In APV RESOLA project, however, it is limited to four different crop species (potato, celeriac, clover grass, and winter wheat), thus many more crops and varieties should be analyzed in order to identify the impacts of APV. In addition, crop yields at different locations should be evaluated as the here in presented results are not necessarily transferable to other locations. In this study, shading has been discussed as the only relevant parameter affecting crop performance of an APV system. However, crop productivity also depends on other factors such as air, soil, temperature, and precipitation [80, 81] agricultural productivity.

Table 2.2: Weather Conditions in southern Germany which close to the location of the APV system [81].

Year	Mean Temperature (°C)	Deviation from 30-year average	Total yearly precipitation ($\frac{1}{m^2}$)	Deviation from 30-year average	Total yearly sunshine [h]	Deviation from 30-year average
2017	10.7	+0.9	978.8	116%	1927.3	113%
2018	11.9	+2.1	616.0	73%	2119.6	124%

With far less moisture and stronger sun irradiation than the year before, the air temperature was noticeably warmer in 2018. (Table 2.2). Shading through APV can obviously be advantageous in dry climates and may enable increased crop yields. This led to higher crop yields of APV for three of the four species—winter wheat, potato, and celeriac—than the reference area. Only clover grass demonstrated comparable outcomes for both years, suggesting that APV does not benefit clover grass even in drier years. The mean LERs of the two years in the current study varied from 1.71 for winter wheat to 1.76 for both celeriac and potatoes, which was obviously greater than the findings from [76]. They estimated LERs between 1.19 and 1.43 as cautious estimates. However, the higher vertical clearance and bifacial modules in the Heggelbach system compared to the studies of [52] may partially account for the system's high LER. Both elements have a considerable impact on the APV system's irradiation conditions.

2.3.4 Monte Carlo Simulation for Agro-PV Project in Malaysia

One of Malaysia's agro-photovoltaic pilot projects, using Java tea as one of the chosen high-value herbal crops, was established at university Putra Malaysia. The Ministry of Science, Technology, and Innovation (MOSTI) launched the initiative as a catalyst to advance green energy in society, as depicted in Figure 2.10 with seven strings of 1 kW PV arrays, the PV array covers an area of 1 acre, taking 20% space buffers from the PV construction and cabling works into account [82]. With a rising value of profit return, this notion of integration displays some good growth progress for the crops that can be supported under PV-shaded situations.

An example of a typical Monte Carlo simulation for agro-photovoltaic projects is used to illustrate the green economy concept for Malaysian growth. The current solar farm operators receive additional financial benefits from the transdisciplinary design of land used and extended to ecological performances, which strengthens the foundation for cooperative cooperation towards the Malaysian green economy.



Fig. 2.10: Launching ceremony by the Minister on December 2015 [82].

2.3.5 Comparative Analysis of Two APV Power Plants in Japan

Japan's rural areas are currently facing pressure from depopulation and over-aging, but a well-designed agro-photovoltaic system might potentially lessen rivalry for land use and create more jobs and revenue. This research work

examines how two conceptual realizations have been implemented in Japan within the current framework. It is computed what the distribution of light is underneath the PV arrays. The two designs differ significantly in the amount of sun light received at ground level (81% and 43%, respectively), as compared to an unobstructed state. In this reasearch, two early examples of representative agro-photovoltaic power plants with distinct designs from Japan are examined. The dispersion of light beneath the solar arrays is analysed with particular attention to establish the viability and extent of agricultural activities on the land [83]. However, Table 2.3 shows the comparison of two agro-PV power plants in Tsukuba, Japan.

Table 2.3: Comparison of Two APV Power Plants in Tsukuba, Japan [83]

Parameter	Project A	Project B
Total rated power	58 kW	20000 kW
PV sub array size	4.5 m × 0.52 m (3×1 modules)	8.30 m × 4.04 m (4×5 modules)
Array arrangement	Single rows with 0.50 m interruptions in E-W direction, 2.52 m pitch of rows in N-S direction	0.20 m between arrays in E-W direction, 6.13 m pitch of rows in N-S direction
PV module size	1.48 × 0.52 m	1.64 × 0.99 m
PV module power	115 W	265 W
Tilt angle	36°, manually adjustable	15°, fixed
Height of PV installation above ground	3.5 m	2.0 m
Orientation	SSW (193°)	S (180°)
PV panel coverage (vertical projection)	19 %	59 %
Proposed agricultural crop	Buckwheat Welsh onion (<i>Allium fistulosum</i>), ...	Shade loving plants: Dokudami (<i>Houttuynia cordata</i>), Ashitaba (<i>Angelica keiskei</i>), Ginseng.

2.3.6 Agro-Photovoltaics Project in Bangladesh

In the Pabna area of central Bangladesh, on 12.5 acres of land, sits the 3.77 MW Soudia Agro Solar PV Power Plant [84]. The project is expected to cost

approximately \$7 million USD. The government will purchase the produced electricity for a 20-year period at a fixed electricity pricing of \$0.1074/kWh.

The developer will implement unique technologies for the many agricultural tasks anticipated on the project's land, which includes five uniquely created solar mounting structures. The land is categorized as typical agricultural productive soil. It said that a significant section of the space beneath the solar panels will be utilized for cultivating nearby chickens, ducks, goats, lambs, bees, and other domestic animals are shown in Figure 2.12. Diverse berry varieties will also be grown in vertical crops, and although no other information was provided, it is anticipated that a greenhouse will be constructed. The combination of solar and agriculture will be the best choice here, considering the scarcity of land in Bangladesh and the high potentiality for solar projects.



Fig. 2.11: Sits of 3.77 MW Soudia Agro Solar PV Power Plant [84].

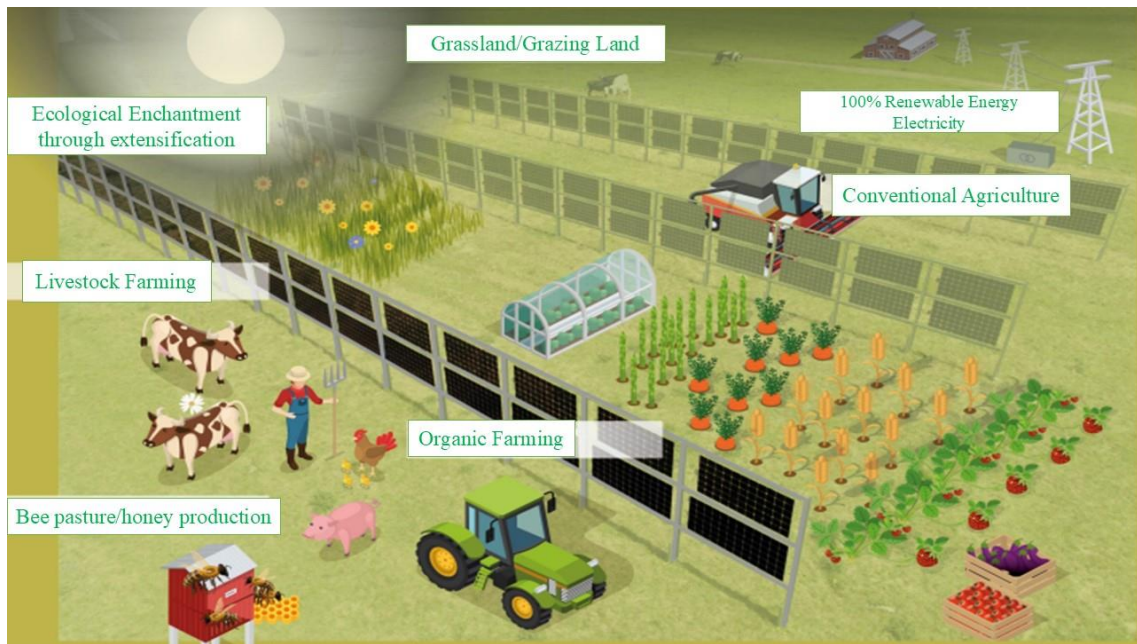


Fig. 2.12: Better network integration and gaining energy yield.

Agro-photovoltaics practices can be carried out in different ways depending on the activities carried out by the population in a given area (Figure 2.11). Agro-photovoltaics applications represent the combination of energy production with (i) agricultural production in the field or (ii) agricultural production in greenhouses or livestock rearing, or (iii) provision of ecosystem services through vegetation management or (iv) different agricultural practices combined.

2.4 AGRICULTURAL LAND USE SCENARIO ALL OVER THE WORLD

Humans' fundamental and most basic requirement is food, and 38% of terrestrial area is used to produce it [85]. Because of the population's rapid rise, there has been a twice-growth in the need for food. There are still some places, though, where food is unavailable. especially the continent of Africa, where 264.2 million people continue to suffer from malnutrition [86]. The UN has a clear plan to end hunger and ensure that everyone has access to food by 2030. More land-based food production is necessary in this situation. Urbanization is a major barrier to exploiting land for food production [87]. The land capacity is decreasing every ten years, as seen in Figure 2.13 It is indisputable that agriculture is the primary source of food.

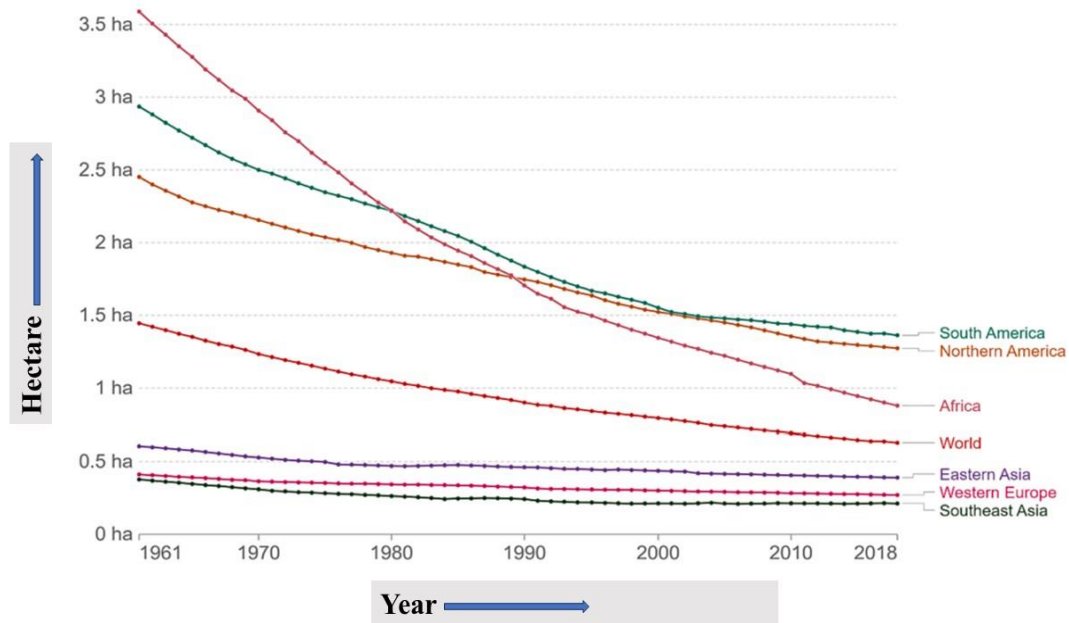


Fig. 2.13: Agricultural land per capita Agricultural land is the sum of cropland and land used as pasture for grazing livestock.

2.5 GRAPES PRODUCTION UNDER DIFFERENT PV MODULES IN APV

The majority of crops in plant APV systems, such as grapes, have a set cultivation orientation. Consequently, at the stage of design, a choice must be made between the cultivation direction of the furrow and the efficiency of power generation. Figure 2.15 depicts the power production pattern of each panel type on July 18, 2019. In this investigation, the direction of module placement impacted the efficiency of power generation rather than module performance. Section A faced south, Section B faced southeast, and Section C faced southwest, as shown by aerial images and schematics of the entire crop in Figure 2.15.

Figure 2.14 depicts the generation data for three distinct PV types. In seven months, the regular module produced 25.2 MWh, the bifacial module produced 21.6 MWh, and the transparent module produced 25.7 MWh. The transparent module generated the most energy, although this was attributable to the orientation of the module. Therefore, it cannot be stated that the transparent module's power-generation performance was higher than that of other modules.

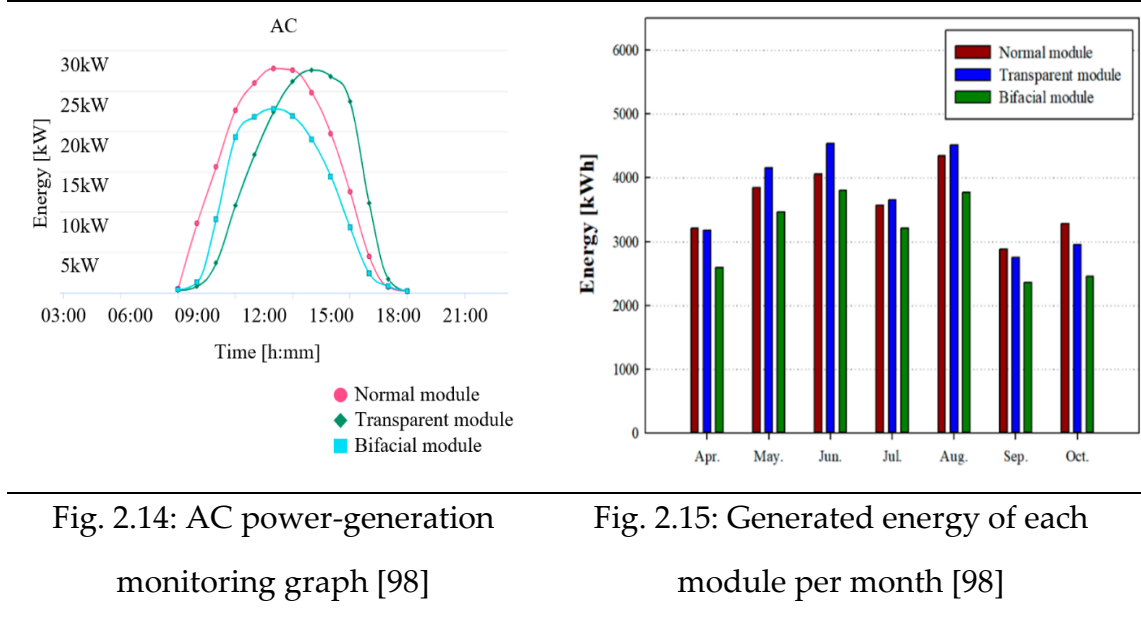
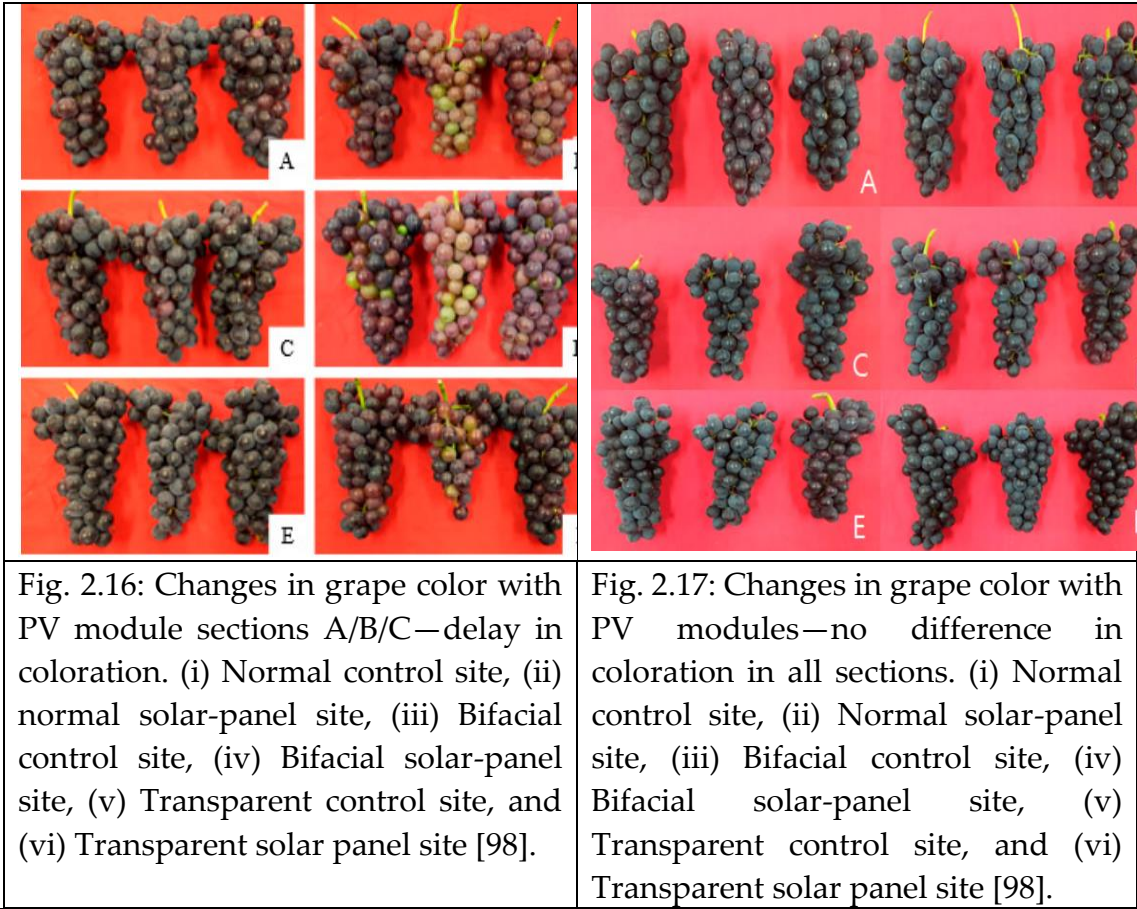


Figure 2.16 and 2.17 shows the changes in grape color with PV module sections A/B/C and changes in grape colour with PV modules respectively.



This study compared the crop-growing environment in a rain-hit protection facility equipped with solar panels to that of a facility without solar panels.

Spring and winter soil temperatures at the experimental location were higher than those at the control site. This was due to a combination of reduced solar radiation and temperature changes resulting from the installation of solar modules. There was no discernible difference between their effects on electricity generation and grape growth. The study may serve as a starting point for more research on the compatibility of renewable energy with agriculture.

2.6 DIFFERENT PV MODULES USES IN APV PROJECT

For both APV and PV-GM, commercially available silicon-based PERC PV module technology was considered, but for the cereal and vegetable production area where APV was used, bifacial PV modules were chosen because this type of PV technology processes both direct and indirect light on the front and back sheets of the PV module. The rear sheet is constructed of glass, allowing light to reach the solar cell from below as well. This indicates that this form of PV module achieves more efficiency and partially compensates for the wider PV module row spacing required to provide adequate light to the agricultural production system. Further advantages of the bifacial modules include compatibility with the state building rules for overhead glass in Baden-Württemberg and the fact that no additional construction measures, such as safety nets, were required to ensure work safety in conjunction with the APV system. In addition, crops planted beneath an APV benefit from diffused light rather than direct shadowing close to the ground shown in Figure 2.18 and Figure 2.19.

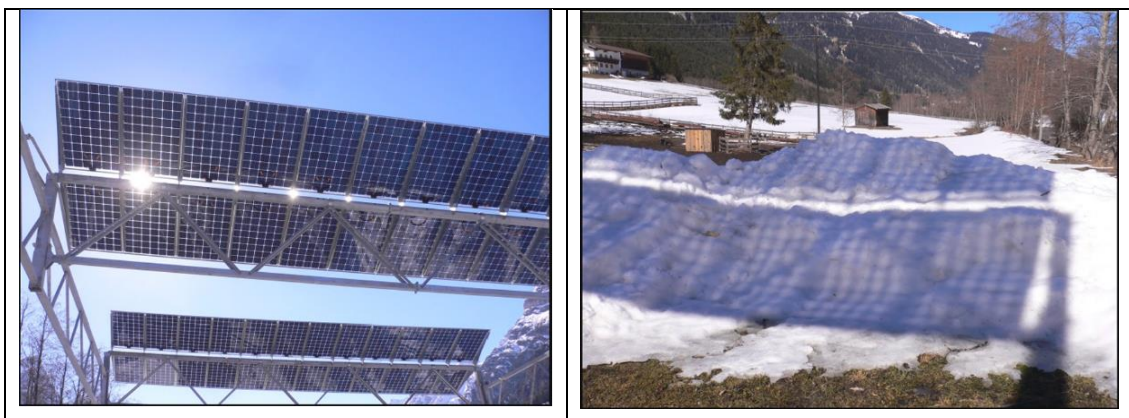


Fig. 2.18: Left: Bifacial glass-glass PV Modules [95].	Fig. 2.19: Diffuse shadows from bifacial PV modules near ground [95].
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Solar panels, both conventional and transparent, were set up in order to determine the effect of shade on the growing environment. Additionally, standard and bifacial modules were fitted to boost the efficiency of electricity generation. The dimensions of the modules were 1476 × 666, 1524 × 686, and 1476 × 780 mm^2 , which is almost half the size of a standard module. Each type of module had an installation capacity of 33 kW, and the test bed's overall solar-power capacity was 99 kW. The orientation of solar modules for agro-photovoltaic systems varies depending on the geometry of the farm's ridge and crop. However, Figure 2.20 shows three types of solar panels. A, normal type; B, bifacial type; C, transparent type which found the experiment site [90]. Consequently, not all modules faced the same direction. Section A's south orientation was maintained via a turntable solar system above a rain-damaged facility, although it is sensitive to typhoons and was more expensive than the solar systems utilized in Sections B and C. Sections B and C were built-in to the roof to compare energy production.

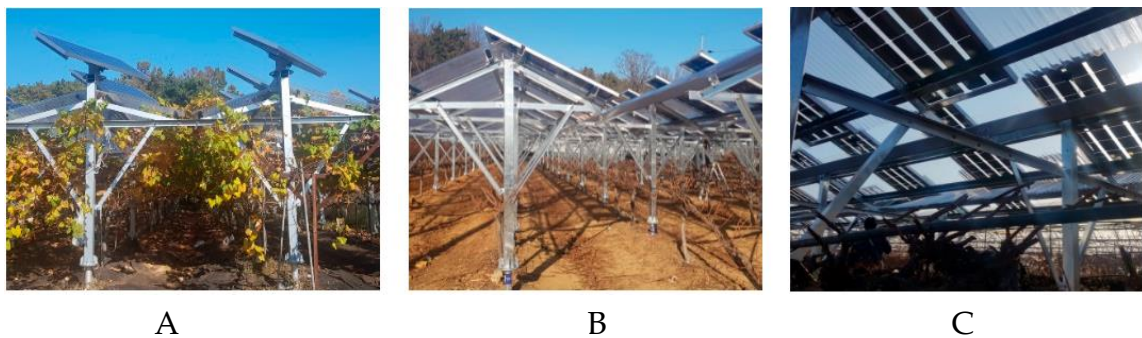


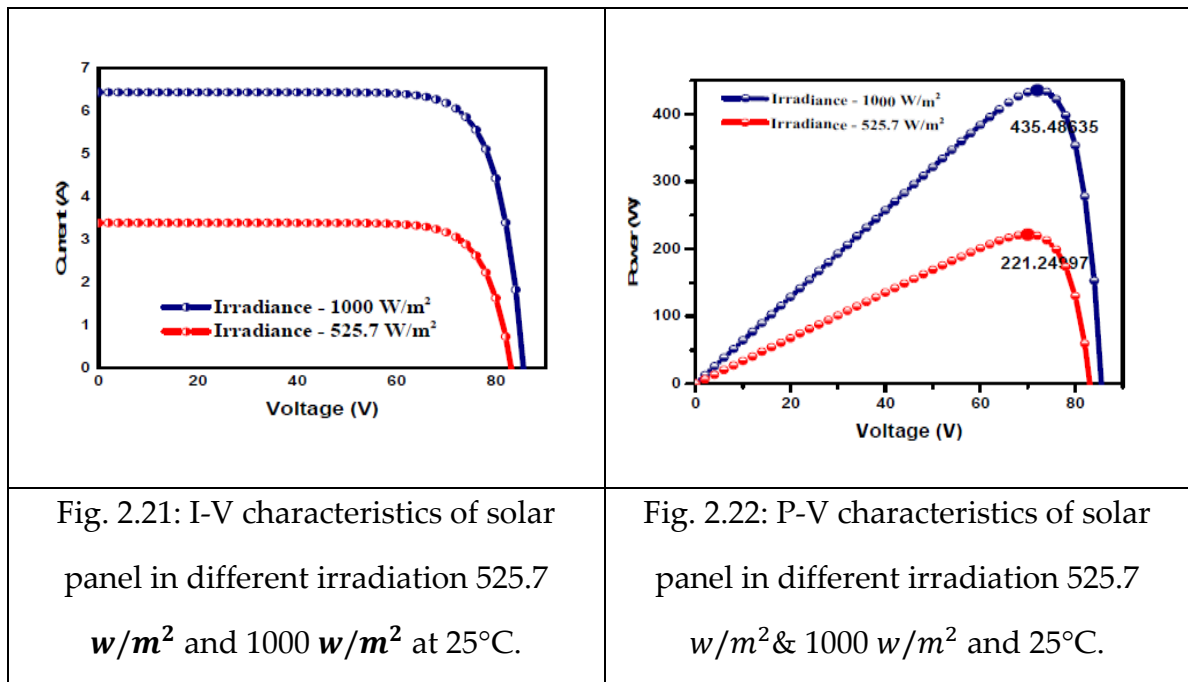
Fig. 2.20: Three types of solar panels. A) normal type; B) bifacial type; C) transparent type [96].

Real-time monitoring of crop-growth-parameter data, including microclimate, soil temperature, soil moisture, solar radiation, and leaf wetness, demands the employment of solar-powered rechargeable batteries with wireless sensors and

robot agents on fields. These sensors have been used well in greenhouses to measure the comfort ratio of microclimate parameters [97], where there is artificial lighting and shadowing is not a problem.

2.7 CHARACTERISTICS OF SOLAR CELL

A solar cell is a forward-biased, large-area diode with a photo voltage. Photo voltage is generated by the dissociation of electron-hole pairs made by incoming photons within the junction or diode's built-in field. Solar or photovoltaic (PV) cells are composed of semiconducting materials that may directly convert sunlight into energy. When sunlight reaches the cells, it dislodges and frees electrons from the material, which then flow to generate a DC current. When light strikes a photovoltaic cell without a voltage bias (i.e., in a short circuit), electron-hole pairs absorb photons and produce a short circuit current (I_{sc}) proportional to the input light. In the presence of both light and voltage bias (i.e., a connected load), the photovoltaic cell current " I " is the difference between the short circuit current and the dark current I_D . Most of the time, shunt resistance is quite high, but the series resistance in the circuit shown in Figure I is quite low. Figure 2.21 demonstrate the Current - Voltage characteristics of solar panel in different irradiation 525.7 W/m^2 and 1000 W/m^2 at 25°C and Figure 2.22 shows the Power -Voltage characteristics of solar panel in different irradiation 525.7 W/m^2 & 1000 W/m^2 and 25°C . However, I-V Characteristics curve is a graphical representation of a solar cell's electrical characteristics. It shows the relationship between the current flowing through the cell and the voltage across its terminals.



2.8 CARBON FOOTPRINT IN APV PROJECT

Regarding stand-alone agro-photovoltaics project, several significant details about the essential element of these systems—namely, the ongoing advancement and present state-of-the-art of solar power plants—need to be addressed. First of all, the extremely low carbon intensity of power generation, measured in grams of CO₂ equivalent per kWh (g CO₂ eq per kWh), gives PVPP, along with other power plants based on renewable energy sources and nuclear power plants, a significant advantage over technologies based on fossil fuels. Figure 2.23 displays the average carbon intensity of electricity generation by technology. PVPP's carbon intensity is declining as a result of improved photovoltaic cells using less energy.

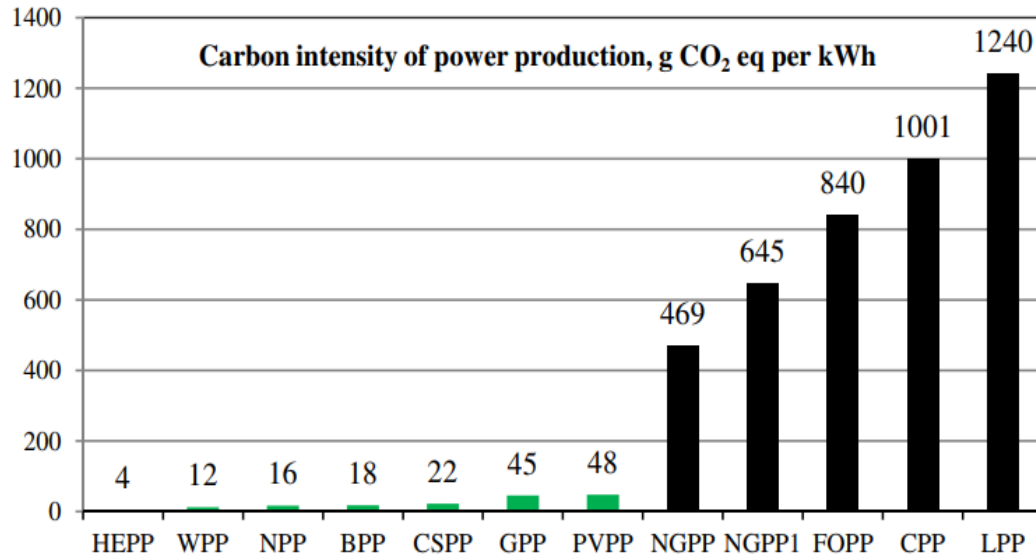


Fig. 2.23. Average carbon intensity of power generation by the technologies [100].

2.9 SUMMARY AND IMPLICATIONS

This chapter discusses state-of-the-art restructuring of the solar PV-based sustainable and clean Renewable Energy based electricity production. Then the chapter describes the Fundamental Technical Parameters of APV System where all components APV describes with recent project of APV system all over the world. Further it highlights the major APV project which implemented both commercial and research facilities such as RESOLA project in Heggelbach, Germany, APV Project in Fraunhofer Institute for Solar Energy Systems ISE, Calculating LER in APV RESOLA Project, also discuss APV project in Bangladesh. Land use scenario all over the world and Grape's production under different PV modules in APV project also discussed. A few papers that are aligned with the work proposed in this research have been critically reviewed. Those papers have been reviewed in-depth by comparing and contrasting the objectives, strengths, and weaknesses. The research gaps and problems have been established.

3 Research Methodology and Modelling

This chapter outlines the research design employed to achieve the aims and objectives defined in Section 1.10 of Chapter 1. It provides an in-depth explanation of the Crops Plantation model under Solar Photovoltaic Panels, exploring its potential benefits and practical implications. Section 3.1 presents an analysis of gardening plantation models, comparing those utilizing shaded areas with those grown in unshaded conditions, while discussing their prospects. Section 3.2 focuses on the implemented Agrivoltaic (APV) system design, detailing its structural and operational factors.

In Section 3.3, the Land Equivalent Ratio (LER) is introduced to evaluate the benefits of stand-alone agrivoltaics in optimizing land use efficiency. Section 3.4 provides an overview of the system's load calculation and the corresponding load profile curve, which are crucial for understanding the energy demands of the proposed design. Section 3.5 delves into a detailed electrical shading analysis, assessing its impact on both photovoltaic performance and crop productivity. Finally, Section 3.6 summarizes the key findings and offers concluding remarks for this chapter.

3.1 CROPS PLANTATION UNDER SOLAR SHADE AND WITHOUT SHADE

This study investigates the integration of agro-photovoltaic (APV) solar energy systems with horticultural crops, including tomato, brinjal, green chili, lettuce, and aloe vera, cucumber, snake-gourd, rose flower both with and without PV shade. The effectiveness of this approach is evaluated using the land equivalent ratio (LER) method.

3.1.1 Proposed Stand-Alone Agro-PV Design

Figure 3.1 represents proposed triangular agro-photovoltaic (APV) system, combining solar panels with agricultural land use. The layout demonstrates the integration of photovoltaic panels positioned strategically to optimize both solar energy generation and agricultural productivity. Crops are grown beneath and around the solar panels, illustrating the synergy between shading-tolerant crop cultivation and renewable energy production. The triangular configuration ensures efficient land use, promoting high Land Equivalent Ratio (LER) by maximizing the dual-use benefits of energy and food harvesting. Also, the triangular shape is selected to optimize partial sunlight exposure, which is crucial for photosynthesis and crop growth. This shape offers several key advantages:

1. Optimal Sunlight Distribution

The triangular structure allows for uniform sunlight distribution across crops. The sloping panels reduce shading on the ground, which is crucial for crops requiring moderate to high levels of sunlight. Additionally, during different times of the day, the triangular orientation ensures that sunlight is distributed more dynamically across the farm.

2. Efficient Use of Space

Triangular configurations enable the installation of PV panels at an angle, which maximizes solar energy capture while leaving sufficient open spaces below for crop cultivation. This dual optimization is particularly valuable in limited land areas where both agriculture and renewable energy are prioritized.

3. Improved Energy Efficiency

Solar panels mounted on triangular structures can be tilted to the optimal angle for solar energy production based on the geographic location. This ensures maximum energy yield throughout the year, especially during peak sunlight hours.

4. Reduced Heat Stress for Crops

The triangular shape allows for shading during the hottest parts of the day, reducing heat stress on the crops beneath the panels. This is particularly beneficial for crops susceptible to high temperatures, as it maintains a cooler microclimate.

5. Structural Stability and Wind Resistance

Triangular designs are inherently stable and can withstand strong winds better than flat or vertical systems. This stability is critical in agricultural settings where equipment and crops need protection from harsh weather conditions.

6. Cost-Effectiveness

Compared to other complex designs, triangular structures are relatively simple and cost-effective to build. The use of fewer materials for support and their ease of assembly makes them a practical choice for large-scale AgroPV installations.

7. Economical Consideration

More economically feasible in dual-purpose systems where both energy generation and crop productivity are critical, as it enhances land-use efficiency and provides better crop yield potential.

Example Applications and Case Studies

- **Japan's Solar-Sharing Farms:** Many of the agrivoltaic installations in Japan use triangular or A-frame designs to optimize land use while producing solar energy and cultivating crops like rice, chili, and lettuce.
- **France's Sun'Agri Projects:** Triangular PV systems have been used to demonstrate improved agricultural yields for sun-sensitive crops such as tomatoes and berries.

The system incorporates three 100-watt solar panels, occupying a total area of approximately 9 m² per the design specifications. The mechanical structure has varying heights, with one side measuring 6 feet 2 inches and the other 5 feet 2 inches, where solar panel dimensions are 31.89 x 28.15 x 1.38 in (810 x 715 x 35 mm) chosen to meet specific design requirements in figure 3.2.

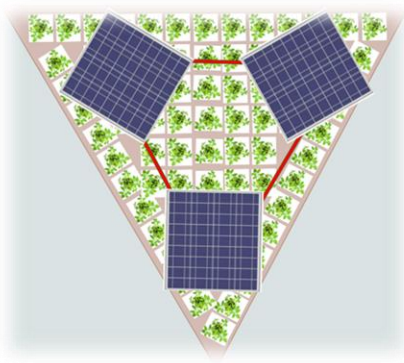


Fig. 3.1: Proposed prototype of SAPV System.

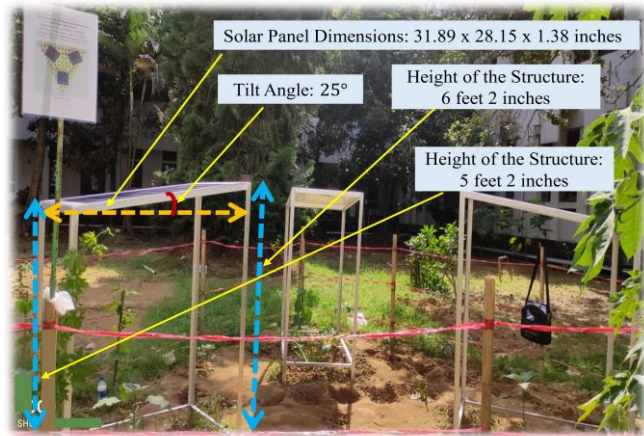


Fig. 3.2: Mechanical structure of APV Project.

Table 3.1: Design specification of APV System

Field Type	Fixed Plane
Plane Tilt	25°
Azimuth	0°
Total Area	9 m ²
Optimization with respect to	Annual Yield
Transposition Factor (FT)	1.07
Global on Collector Plane	1707 KWh/m ²

Table 3.1 is configured with a fixed tilt of 25° and south-facing orientation (0° azimuth), optimized for maximum annual energy yield with no losses due to suboptimal settings. The system has a module area of 9m² comprising 3 modules, receiving an annual global irradiation of 1707 kWh/m². The transposition factor is 1.07, indicating enhanced energy capture due to the tilt, and the configuration is validated as optimal for deployment. However, Table 3.2 demonstrates the necessary information of the Solar Panel Mechanical Specification.

Table 3.2: Selected Solar Panel Mechanical Specification

Specification	Parameter
Cell Size	6.54 x 3.27 in (166 x 83 mm)
Solar Panel Dimensions	31.89 x 28.15 x 1.38 in (810 x 715 x 35 mm)
Number of Cells	36
Weight	15.4 lbs (7 kg)

Mounting Hole Dimensions	0.35 x 0.55 in (9 x 14 mm)
Cable Length	47.2 in (1200 mm)
Connector Type	MC4 Compatible
Junction Box	IP65
Rated Snow / Wind Load	50 bs/ft2

3.1.2 Photosynthesis Rate (PN) of Proposed Crops

Table: 3.3: Photosynthesis Rate (PN) of the proposed Crops

Crop	Photosynthesis Rate (PN)	Details	Reference
Tomato	10–15 $\mu\text{mol CO}_2/\text{m}^2/\text{s}$	Optimal rates observed under moderate light and CO_2 concentration levels.	[110]
Brinjal	8–12 $\mu\text{mol CO}_2/\text{m}^2/\text{s}$	Rates influenced by temperature and light; optimal in 25–30°C environments.	[111]
Green Chili	12–16 $\mu\text{mol CO}_2/\text{m}^2/\text{s}$	Higher rates under increased red-blue spectrum lighting.	[112]
Lettuce	6–9 $\mu\text{mol CO}_2/\text{m}^2/\text{s}$	Grown in controlled environments; rates decrease under low light stress.	[113]
Aloe Vera	3–5 $\mu\text{mol CO}_2/\text{m}^2/\text{s}$ (CAM Plant)	Lower daytime photosynthesis; CO_2 fixation occurs primarily at night.	[114]
Cucumber	16–20 $\mu\text{mol CO}_2/\text{m}^2/\text{s}$	High rates observed under 90% red and 10% blue light in controlled settings.	[115]
Snake Gourd	9–14 $\mu\text{mol CO}_2/\text{m}^2/\text{s}$ (approx.)	Based on general Cucurbitaceae family traits; direct data scarce.	[111]
Rose Flower	5–7 $\mu\text{mol CO}_2/\text{m}^2/\text{s}$	Moderate rates linked to decorative flowering plants grown in greenhouses.	[116]

- ✓ Variability in the photosynthesis rate depends on factors such as light intensity, temperature, and plant health.
- ✓ CAM (Crassulacean Acid Metabolism) plants like Aloe Vera show lower daytime photosynthesis rates as they fix CO_2 primarily at night.
- ✓ **Tomato and Brinjal:** Values include studies from general horticulture under diverse conditions for comparison.

- ✓ **Aloe Vera:** Highlighted as a CAM plant, where CO₂ uptake is restricted during the day.
- ✓ **Cucumber:** Emphasized its high photosynthetic efficiency under specific light spectra (90% red, 10% blue).

3.1.3 Basic Block Diagram and Typical Layout of SAPV System

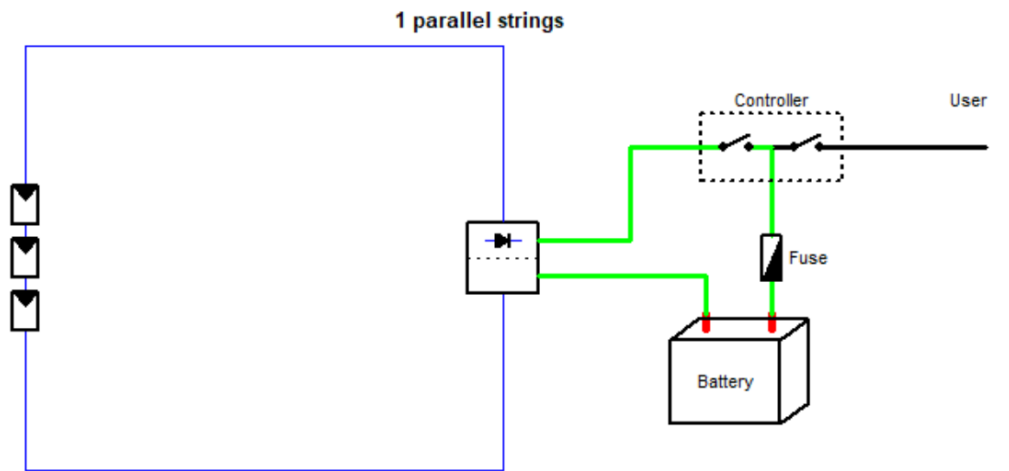


Fig. 3.3: Single Line Diagram of Proposed Model.

Figure 3.3 illustrates a proposed photovoltaic system with one parallel string of PV modules. The generated DC power flows through a blocking diode to prevent reverse current and charges a battery for energy storage. A controller regulates power flow to ensure battery protection against overcharging or deep discharge. The fuse safeguards the system against overcurrent conditions, while the load is powered through the controller.

Typical layout of a stand-alone system

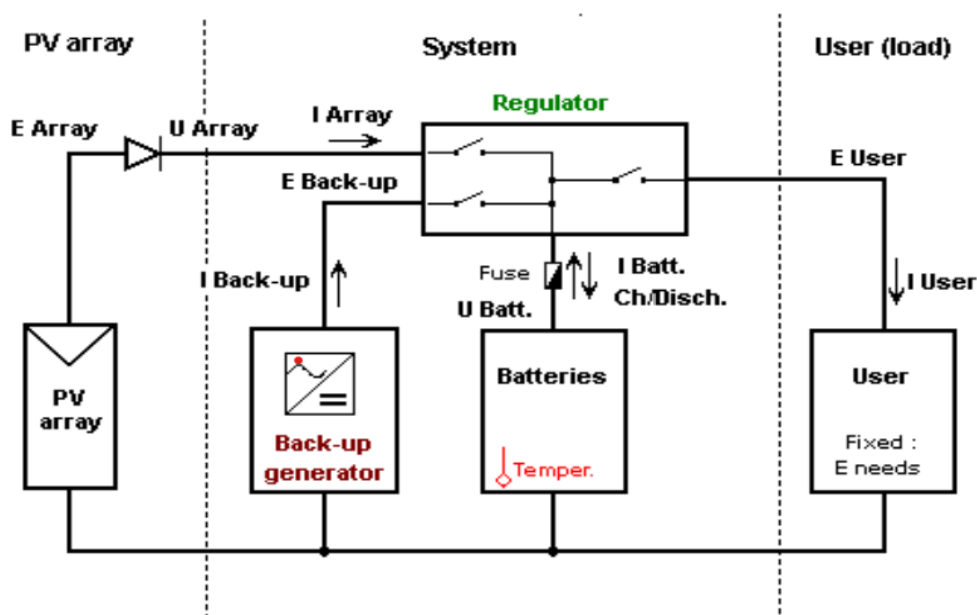


Fig. 3.4: Typical Layout of Stand-alone system.

Figure 3.4 represents a typical layout of a stand-alone photovoltaic (PV) system generated from PVsyst software, showcasing the integration of a PV array, batteries, a regulator, where backup generator is not considered. The PV array converts solar energy into electrical energy, which is regulated before being directed to the user load or stored in the battery system. A regulator ensures proper energy distribution and prevents overcharging or discharging of the batteries.

3.1.4 Location Details and Metrological Data of this APV Project

Figure 3.5 display satellite and street views, respectively, of the proposed site located within the EME building premises at Chittagong University of Engineering & Technology (CUET). The site is situated at a latitude of 22.46°N and a longitude of 91.97°E, with an altitude of 29 meters and an albedo of 0.20. This location offers excellent solar radiation potential and is protected by surrounding square-shaped buildings, ensuring safety from cattle and other animals. At this site, the maximum solar irradiation is recorded in March, April,

and May, with values of 166 kWh/m², 165 kWh/m², and 164 kWh/m², respectively. Additionally, the monthly average temperature is 25.12°C.



Fig. 3.5: Project implementation area, Premises of EME Building, CUET a) Satellite view, b) Street View.

3.1.5 Solar Horizon of the Proposed APV System

Solar Horizon of the proposed APV system depicted in Figure 3.6 which demonstrates how much sun is truly accessible. The red line indicates shading around the solar-powered field, primarily from distant trees, while the blue line corresponds to the photovoltaic modules automatic shading. For PV power generation solar irradiance and temperature plays an important role.

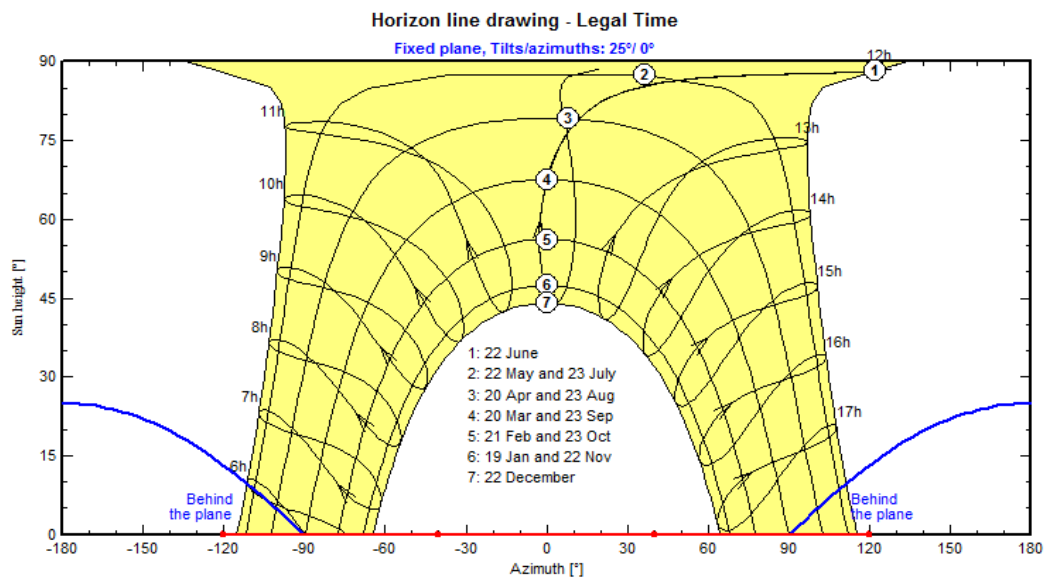


Fig. 3.6: Solar Horizon of the proposed APV System.

3.1.6 Monthly Average Solar Irradiance and Temperature

In Figure 3.7 shows available irradiation in the proposed site is where March, April, May shown the maximum solar irradiation respectively 166 kwh/m^2 , 165 kwh/m^2 , 164 kwh/m^2 . On the other hand, Figure 3.8 shows the monthly average temperature in proposed site is 25.12°C .

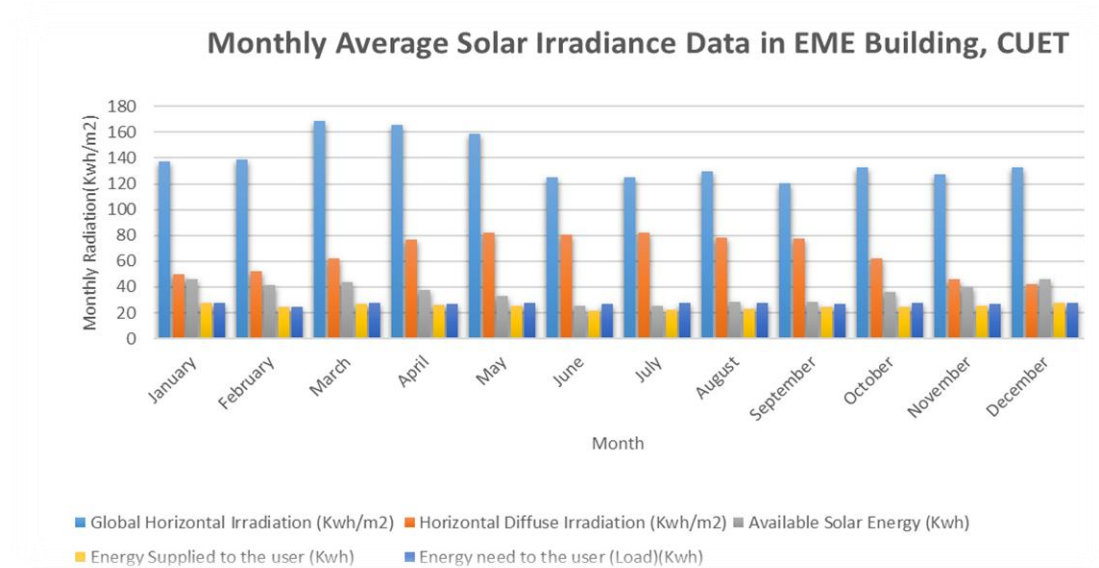


Fig. 3.7: Monthly average solar irradiance data in the Premises of EME Building, CUET.

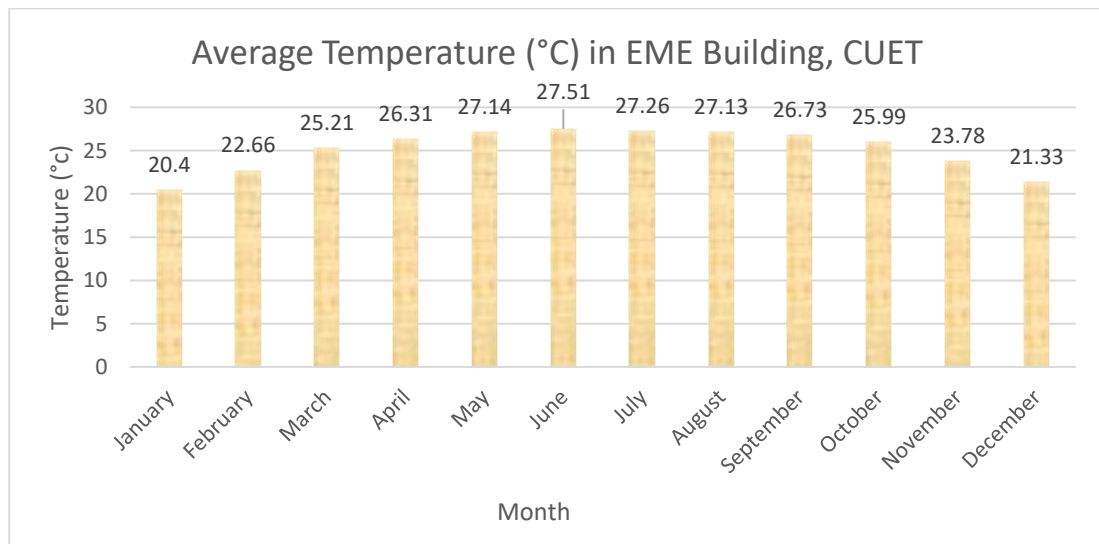


Fig. 3.8: Monthly average temperature in the Premises of EME Building, CUET.

3.1.7 Performace Characteristics of Photovoltaics

In Figure 3.9, I-V curve depicts the performance characteristics of a photovoltaic (PV) comprising three modules in series and one string in parallel under 800 W/m² irradiance. The maximum power point (PMPP) of the PV is 237 W at a module temperature of 25°C, with losses attributed to various factors. Key losses include module quality (-0.7%), mismatch (-2.1%), and IAM due to diffuse and beam radiation (-1.8%). Elevated temperatures (41.3°C) and wiring resistance (144 mΩ) contribute further losses of -5.6% and -1.3%, respectively, culminating in a global loss of 7.7% and a resultant PMPP of 219 W.

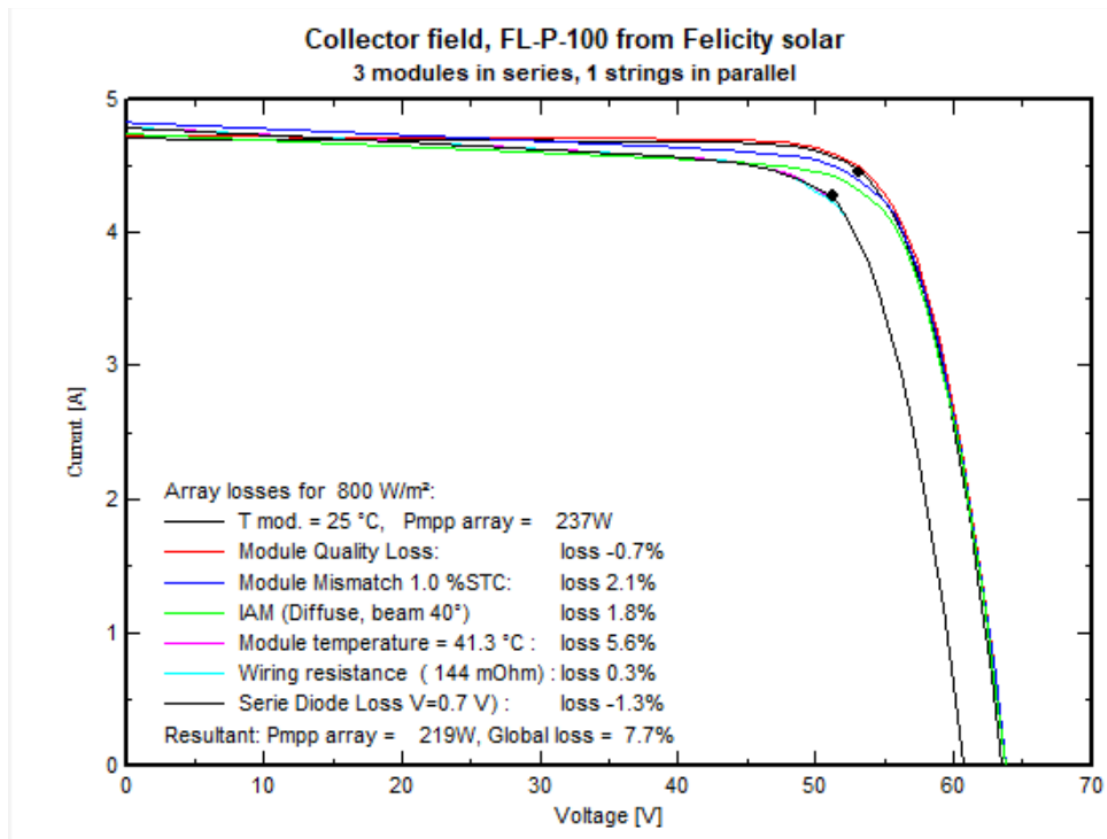


Fig. 3.9: I-V Characteristics of PV Array.

3.1.8 PV Module Configuration and Battery Storage

The size of PV arrays depends on the solar radiation available [101]. A large number of solar modules are connected to make arrays [102]. The PV array should be appropriately sized to provide enough energy to the loads and to charge the battery. Table 3.4 shows the electrical parameters of the PV panel and

battery system used in the SAPV model. The PV array needs to be placed at a certain angle to receive the maximum amount of solar radiation. For a fixed PV array, typically, the array needs to be oriented to face south in the Northern hemisphere. Optimum PV array output can be achieved using a tilt angle approximately equal to the site's latitude. The tilt angle is studied 25° in this project. The design principle for sizing the system's battery was to compensate for daily solar radiation variations and not act as seasonal energy storage [103]. The details of all the specifications of the battery set used during the design of the PV system are shown in Table 3.4.

Table 3.4: Selected Solar Panel and Battery System Specifications.

Specifications	Standard Parameter	Specifications	Standard Parameter
Type of PV Module	Polycrystalline	Battery Technology	Lead-acid, sealed, AGM
Panel Model	FL-P 100	Battery Model	PVX-890T
Nominal Power (P_{nom}) (STC)	100×3=300 W (Three panel)	Discharging min. SOC	20.0 %
Max. operating power (P_{max})	237 W	Battery Voltage	12 V
Maximum Current (I_{mp})	5.6 A	Nominal Capacity	80 Ah
Maximum Voltage (V_{mp})	49 V	Temperature	20 °
Modules	1 string × 3 in series		

3.2 IMPLEMENTED APV DESIGN & DESIGN FACTORS

Figure 3.10 illustrates Implemented APV Project in EME Building premises, CUET (Top View) and Crops plantation under Solar Shade in APV system (side view). The project study of various crops, including aloe vera, tomato, brinjal, green chili, and lettuce, cucumber, snake-gourd and rose flower. These crops were planted in equal proportions under solar shade and non-shade conditions. They were examined based on plant height, number of leaves, quantity of flowers and fruits, and the weight of fruits, both under solar PV systems and without PV. As a design factor, we considered three plants, both under partial shade and full sunlight, with a focus on maximizing crop output rather than optimizing the

solar PV system. The energy yield of Agrivoltaics (APV) systems differs from that of ground-mounted PV systems due to several key design factors. Here the main design factors considered in this project are:

- **Partial shade:** APV systems are designed to balance the need for crop shade with solar energy generation. While partial shade helps prevent crop overheating and encourage healthy growth, it can also reduce the overall energy yield.
- **Row Spacing:** To guarantee that crops receive enough sunlight, APV systems frequently have rows of panels spaced farther apart than ground-mounted systems. This may result in a decrease in the overall area that is covered by panels and the energy yield.
- **Dual-Use Considerations:** APV systems are made for dual-use, which means that agricultural and energy production share the same area. This means making design compromises that may lower energy output, including less dense panel layouts.
- **Temperature Effects:** Because of the shade that crops produce, the ground beneath APV systems may be colder than that of underground-mounted PV systems. PV panels can operate more efficiently at lower temperatures.



Fig. 3.10: (a) Implemented APV Project in EME Building premises, CUET (Top View), (b) Crops plantation under Solar Shade in APV system.

3.3 THEORETICAL BACKGROUND OF APV: LER TECHNIQUE

The LER concept, first introduced by Mead and Willey, is widely used in aquaponics, agroforestry, and most recently, APV, to measure the land use efficiency of intercropping systems [104]. The Land Equivalent Ratio (LER) is a measuring parameter used in APV to assess the efficiency of intercropping systems compared to sole cropping [33]. It quantifies the relative advantages of growing multiple crops together in the same space compared to growing them separately [105]. Land Equivalent Ratio defines as eq (3.1), where $Yield\ of\ plants_{APV}$ indicates Grain yield in APV system (kg/m^2), $Yield\ of\ plants_{no\ PV}$ indicates Grain yield in full light scenario (kg/m^2), $Electricity\ Yield_{APV}$ indicates Electricity yield in APV scenario from PV (kwh/m^2), $Electricity\ Yield_{only\ PV}$ Indicates Electricity yield in a ground-mounted scenario from PV (kwh/m^2).

$$LER = \frac{Yield\ of\ plants_{APV}}{Yield\ of\ plants_{no\ PV}} + \frac{Electricity\ Yield_{APV}}{Electricity\ Yield_{only\ PV}} \quad (3.1)$$

The second component of the Land Equivalent Ratio (LER) eq (3.1) represents the relative energy yield of agrivoltaics (APV) systems compared to traditional ground-mounted PV systems. Bangladesh's annual average solar insolation ranges between 4 and 6.5 kWh/m²/day, positioning the country as an ideal location for solar PV systems. **Based on this solar potential, a 300-watt PV system could generate approximately 1.2 to 2 kWh of electricity per day under optimal conditions**, taking into account system efficiency losses due to factors such as temperature effects, wiring inefficiencies, and inverter losses [117], [118]. It is calculated triangular shape APV yield is equivalent to square shape ground mounted PV yield in same area. This factor is influenced by several key design and environmental factors:

- **Shading Effects:** Seasonal variation in shading, particularly during winter months when the sun's angle is lower, can significantly impact the energy yield of APV systems relative to ground-mounted systems [32].

- **Temperature Effects:** Temperature fluctuations, especially in warmer months, can decrease the efficiency of PV panels in APV systems compared to ground-mounted systems, which typically have better cooling due to direct contact with the ground [31].
- **Solar Radiation Intensity:** Seasonal changes in solar radiation intensity directly affect the electricity yield of APV systems, with the most significant impacts observed during summer and winter months [33].

However, decision-making can be possible using the following prospective output.

- If $LER > 1$, the APV system has Yield Advantages.
- If $LER = 1$, the APV system has no Yield Advantages.
- If $LER < 1$, the APV system has Yield disadvantages.

3.3.1 LER Calculation in SAPV System

Here, Land Equivalent Ratio are calculated using total eight crops such as tomato, brinjal, green chili, lettuce, cucumber, alo vera, snake-gourd, and rose flower under solar PV and without PV.

- ✓ **LER_{Tomato} :** In the APV system, 0.7 kg of tomatoes are detected where 1.75 kg are produced absence of PV. On the other hand, electricity yield in the APV system is 1.157 kWh, and electricity production without the APV is 1.96 kWh. Using 3.1 equations, the land equivalent ratio in terms of Tomato is calculated at 1.
- ✓ **$LER_{Brinjal}$:** Yields of plants in APV and without PV are 2 kg and 1.5 kg, respectively. On the other hand, electricity yield in the APV system is 1.157 kWh, and electricity production without the APV is 1.96 kWh. Using 3.1 equations, the land equivalent ratio in terms of brinjal is calculated at 1.93.
- ✓ **LER_{Pepper} :** 0.44 kg of green chili is found in the APV system, whereas without PV tomato yield is 0.11 kg. Also, the electricity yields in APV and

without PV are 1.157 kWh and 1.96 kWh, respectively. Using equation 3.1, LER in terms of Green Chili is calculated as 0.96.

- ✓ **$LER_{Lettuce}$** : Yields of plants in APV and without PV are 0.5 kg and 0.4 kg, respectively. On the other hand, electricity yield in the APV system is 1.157 kWh, and electricity production without the APV is 1.96 kWh, using 3.1 equations, the land equivalent ratio in terms of Lettuce is calculated at 1.85.
- ✓ **$LER_{Cucumber}$** : 0.6 kg of Cucumber is found in the APV system, whereas without PV tomato yield is 1.15 kg. Also, the electricity yields in APV and without PV are 1.157 kWh and 1.96 kWh, respectively. Using equation 3.1, LER in terms of cucumber is calculated as 2.1.
- ✓ **$LER_{Alovera}$** : Yields of plants in APV and without PV are 1.9 kg and 1.5 kg, respectively. On the other hand, electricity yield in the APV system is 1.157 kWh, and electricity production without the APV is 1.96 kWh, using 3.1 equations, the land equivalent ratio in terms of Alo vera is calculated at 1.86.
- ✓ **$LER_{snake-gourd}$** : 1 kg of snake-gourd is found in the APV system, whereas without PV tomato yield is 3 kg. Also, the electricity yields in APV and without PV are 1.157 kWh and 1.96 kWh, respectively. Using equation 3.1, LER in terms of snake-gourd is calculated as 0.93.
- ✓ **$LER_{Rose Flower}$** : Yield of plants in APV and without PV are 2 piece and 1 piece, respectively. On the other hand, electricity yield in the APV system is 1.157 kWh, and electricity production without the APV is 1.96 kWh, using 3.1 equations, the land equivalent ratio in terms of Rose Flower is calculated at 2.6.

3.4 LOAD CALCULATION & LOAD PROFILE CURVE OF THE PROPOSED SYSTEM

For this SAPV system used DC load such as Irrigation motor, LED light, and Table Fan. However, load data and daily energy consumption of the 300-W SAPV project is shown in Table 3.5. Based on the data, the daily energy consumption is recorded at 1146 Wh, necessitating the use of three 100 W solar panels. For energy storage during periods without sunlight, an 80Ah, 12V lead-acid battery has been chosen as the storage solution.

Table 3.5: Load Data and Daily Energy Consumption

Load	Types of Loads	Quantity	Power (Watt)	Total Power (Watt)	Use Hours/Day	Energy Wh/Day
Table Fan	DC	1	5W	5W	10	50
LED Light	DC	4	20W	80W	11	880
Irrigation Motor	DC	1	72W	72W	3	216
				157 Watt		1.146 kWh/day

According to Table 3.3, total estimated load 157 W where daily energy consumption in January is **1.146 kWh/day**. A calculation is shown to meet the load and backup requirements.

➤ DC Current Required: $P = V \cdot I$ $I = P/V$ $= 157/12$ $= 13.08 \text{ A}$	➤ Battery Size Selection in Ah $= \frac{w \cdot h}{v}$ $= \frac{\text{Total Load} \cdot \text{Back-up in time Hours}}{\text{Battery Voltage}}$ $= \frac{157 \cdot 6}{12}$ $= 78.5 \text{ AH.}$
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➤ Battery Charging Current $= \frac{\text{Battery Size (AH)}}{10}$ $= \frac{78.5 \text{ AH}}{10}$ $= 7.85 \text{ A.}$	➤ No. of Panel Required $= \frac{293.02}{100} \text{ (Each panel 100W)}$ $= 2.93 \approx 3 \text{ Panel.}$
➤ Solar Plates Power = V*I $= 14 * 20.93$ (Where 14 is the actual voltage of the panel) $= 293.02 \text{ W}$	

According to above calculation for daily energy consumption is **1.146 kWh**, three panel is required where each panel estimated 100 W. To provide electricity in the absence of sunlight, a 12V, 80Ah lead acid battery is selected as the energy storage device. The battery has a worldwide capacity of 2080 Ah and a stored energy of 20.0 kWh (80% DOD). In addition, the total energy stored during the battery's life cycle would be 17086 kWh. The system is equipped with maximum power point tracking (MPPT) based charge controller to regulate battery charging and discharging.

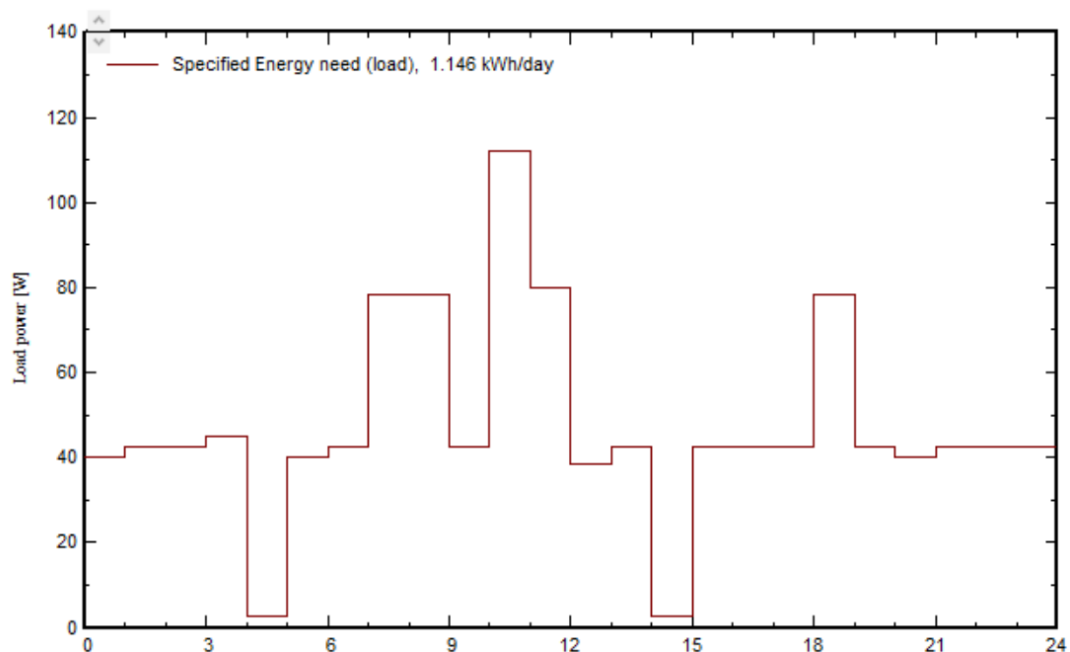


Fig. 3.11: Hourly Load Profile Curve

Figure 3.11 illustrates the hourly load power profile for a system with a total daily energy demand of **1.146 kWh/day**. The load varies throughout the day, peaking at approximately **120 W** during specific hours, with lower consumption levels in the early morning and late evening. Periods of zero load indicate inactivity or no power demand during those hours.

3.5 SHADDING ANALYSIS

In practical agro-photovoltaic (APV) systems, solar panels are frequently shaded by leaves, which significantly reduces their power output [33]. This shading effect prevents the panels from achieving optimal performance. To address this issue, a study was conducted on the electrical impact of shading in APV systems. Measurements of voltage, current, and power were taken both with and without shading to evaluate the variations in performance under these conditions.

3.5.1 Shading Effects on Energy & Crops Yield

The Figure 3.12 illustrates a 3D layout of a 300 Watt Agro-Photovoltaic system, integrating solar panels with agricultural activities beneath. The triangular arrangement of PV modules is designed to maximize solar energy capture while allowing sunlight to penetrate for crop growth. The shading from trees is also incorporated into the layout, providing a realistic representation of partial shading effects on the crops and PV modules. This setup highlights the balance between energy production and sustainable agricultural practices, showcasing efficient land use while mitigating shading impacts on both systems. For the 300-watt agro-photovoltaic (APV) project, PVSyst software plays a critical role in generating comprehensive shading data to assess and optimize system performance.

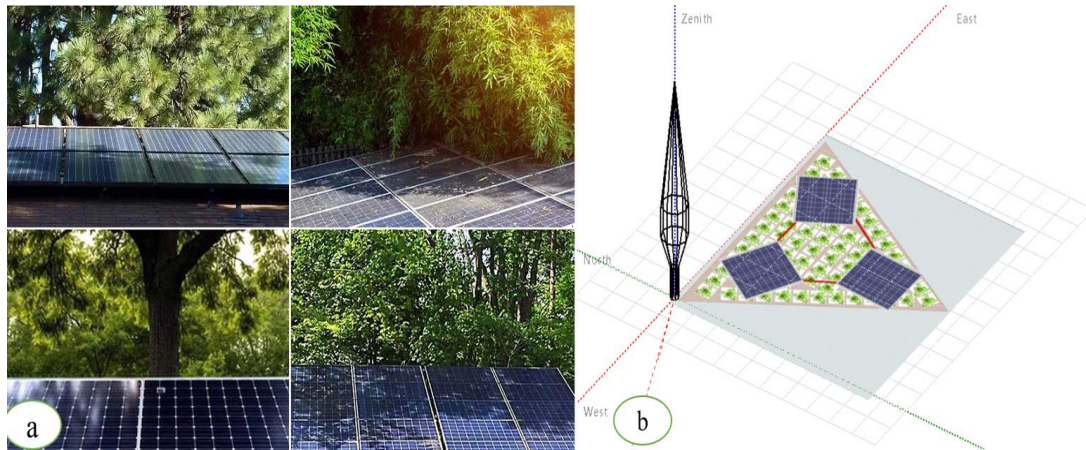


Fig. 3.12: a) Trees Overshadowing Solar Panels, b) 3D design of APV where tree shading Impacts on Energy & Crops yield.

The shading data includes:

1. **Near Shading Analysis:** The software creates a detailed 3D model of the PV array and surrounding environment, including potential shading obstacles such as crops, support structures, or nearby buildings. It calculates shading factors for beam and diffuse irradiation using high-resolution interpolated tables. This simulation allows for dynamic shadow animations to observe shading effects across different seasons and times of the day, critical for understanding how shading impacts energy generation.
2. **Shading Loss Factors:** PVsyst estimates shading losses across beam, diffuse, and global irradiation components. It incorporates the non-linear electrical effects caused by partial shading, considering the PV module's internal wiring layout. This ensures an accurate calculation of shading-induced power losses, helping to define an upper limit for such impacts.
3. **Iso-Shading Curves:** These curves provide visual representations of shading factors along the sun's trajectory, offering insights into the intensity and duration of shading throughout the year. These diagrams enable precise planning to minimize shading and maximize energy output.

By integrating these shading analyses, the 300-watt APV project ensures optimal design and performance, balancing agricultural productivity with efficient energy generation.

3.5.2 Layout of Electrical Shading Analysis

Here Figure 3.13 and Figure 3.14 shows the block diagram and schematic circuit diagram arrangement of electrical shading analysis.

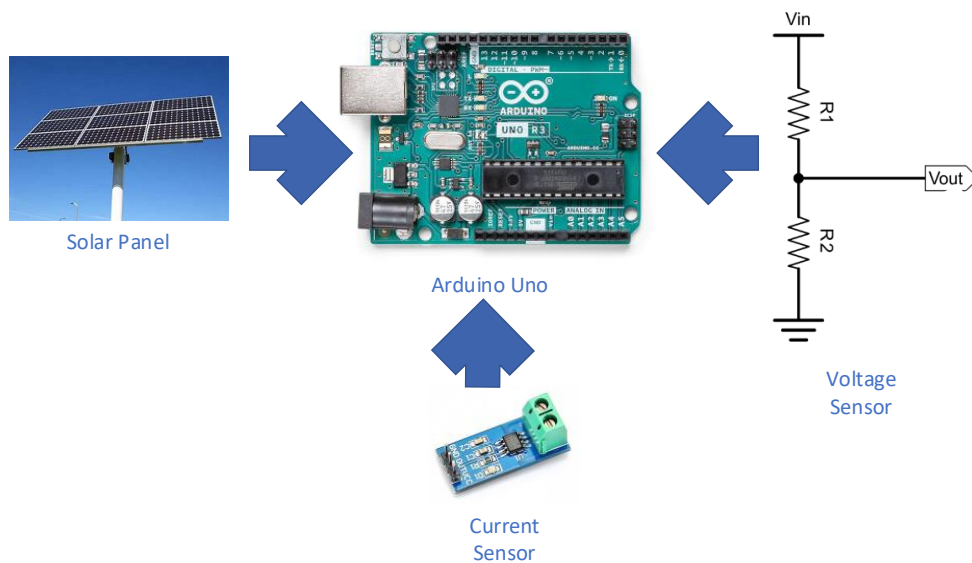


Fig. 3.13: Block Diagram of Electrical Shading Analysis

Moreover, we used three solar panel connected in series, each consist of 16 volts. We have used an Arduino Uno microcontroller to read and process the data, and here also used an ACS712, 30 A current sensor to measure the current. The hall effect sensor detects the incoming current through its magnetic field. Once detected, the hall effect sensor generates a voltage proportional to its magnetic field then used to measure the amount of current. For voltage measurement, we have used a simple circuit with the help of the voltage divider role (VDR). By which we can measure out variable voltages very easily. We can view our data on an Arduino serial monitor after counting it. Calculated the electrical power using the ($P=VI$) formula. After that, collected each data point from the serial monitor and put them on excel sheets manually to create variations of voltage, current, and power plots.

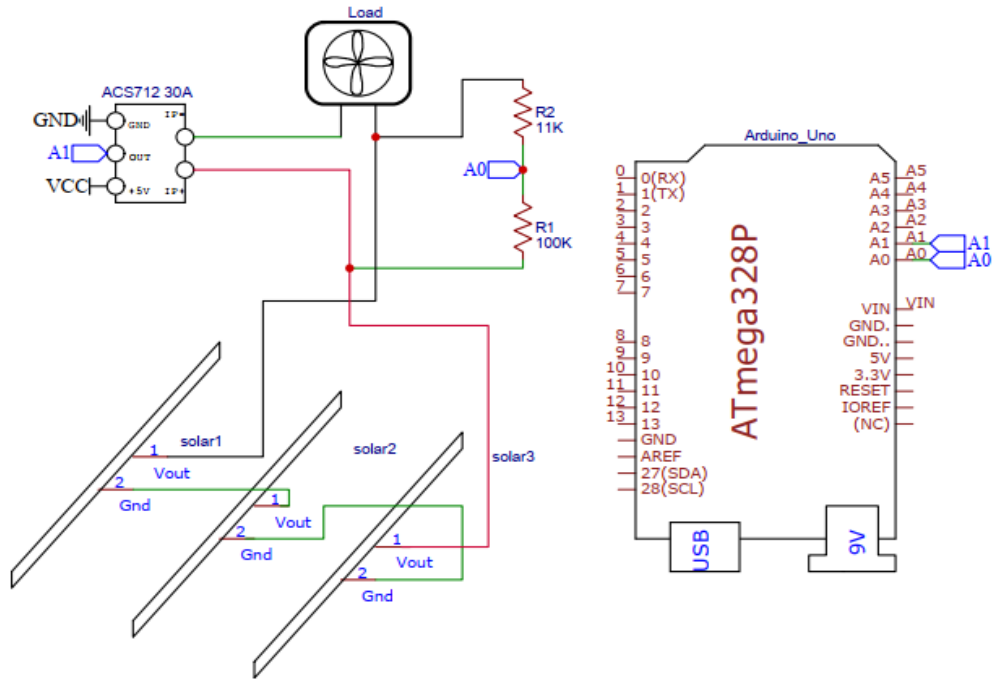


Fig. 3.14: Schematic Circuit Diagram Solar Panel Shading Analysis.

3.5.3 Solar Panel Shading Analysis of this SAPV System

In real-life scenarios, climbing plants can significantly reduce the power output of solar panels by causing shading, thereby minimizing electrical power production in agro-photovoltaic (APV) systems. To address this issue, various solutions were studied and verified through shading analysis in a 300-watt capacity APV project. The system utilized three 100-watt solar panels to power three types of loads: a DC table fan, five DC lights, and a 12V DC irrigation motor. The shading analysis involved evaluating the impact of partial shading, where one solar panel was covered by 33.3%, and two panels were covered by 66.6%. Figure 3.15 shows a typical arrangement of shading analysis where a) 0% shade, b) 33.3% shade, c) 66.6% shade, d) 100% shade. This study highlights the importance of mitigating shading effects to optimize energy generation in APV systems.

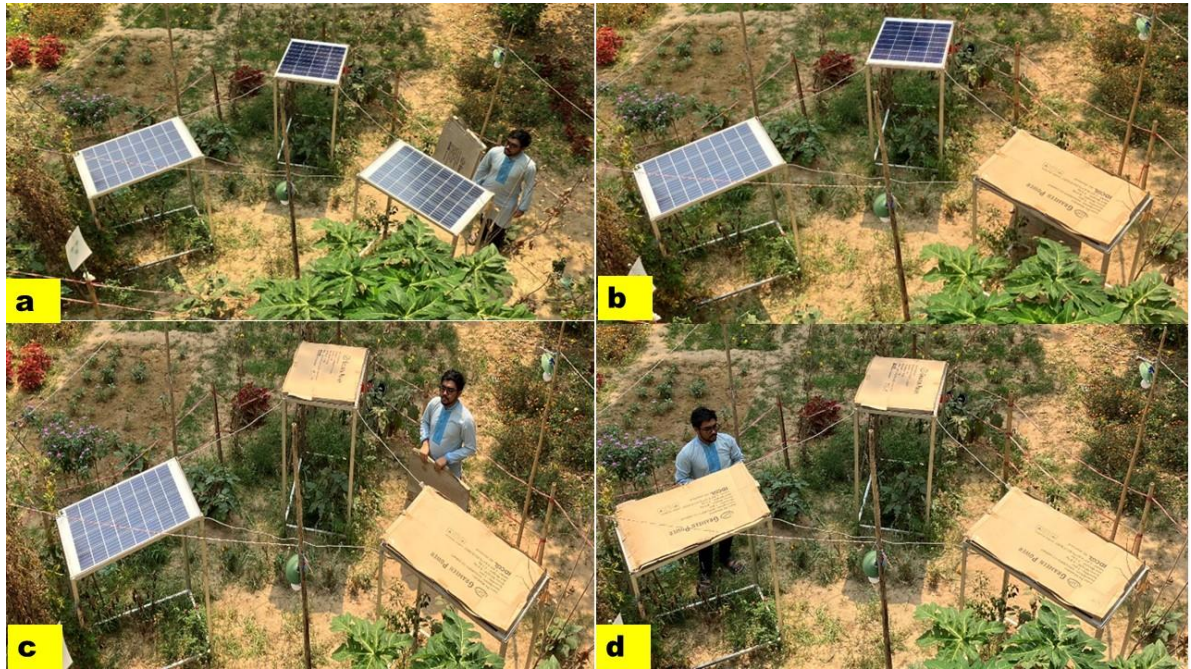


Fig. 3.15: A typical arrangement of shading analysis a) 0% shade, b) 33.3% shade, c) 66.6% shade, d) 100% shade.

3.5.4 Setup for Data Acquisition in Real Time

Figure 3.16 shows some practical views of collected each data from the serial monitor.

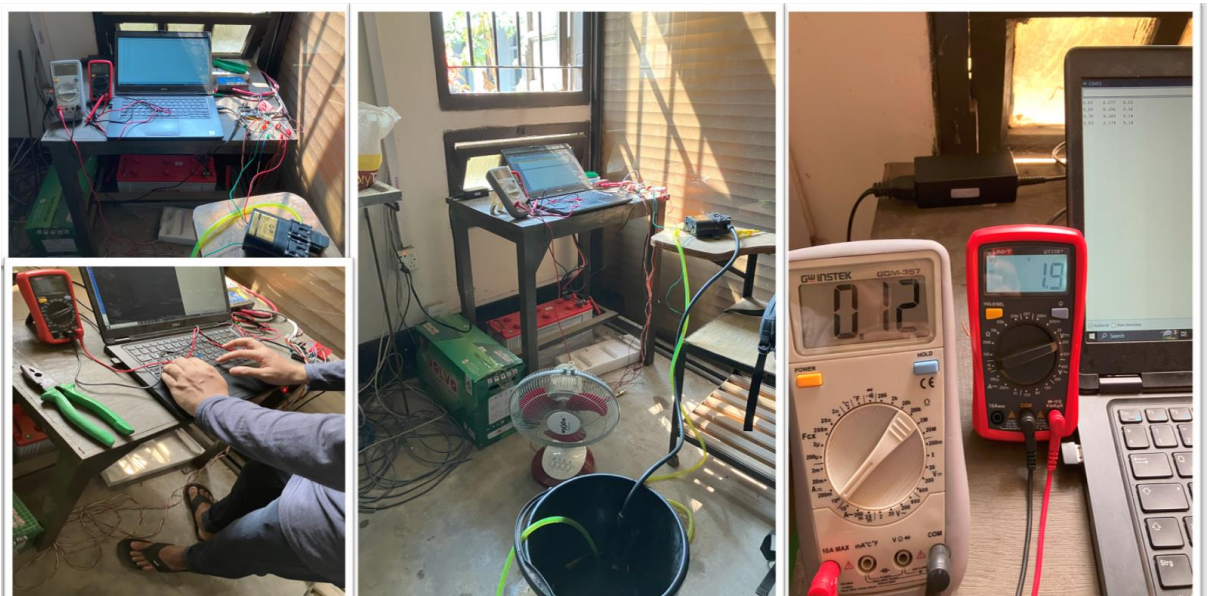


Fig. 3.16: Testing and auxiliary setup for data acquisition in real time

3.6 SUMMARY AND CONCLUSIONS

This chapter outlines the research methodology and modeling of the agro-photovoltaic (APV) system. It begins by discussing gardening plantation models under shaded and non-shaded conditions, highlighting their prospects. The chapter then provides a detailed overview of the implemented APV design, including location specifics, meteorological data of the project area, the solar horizon of the proposed system, monthly average solar irradiance and temperature at the site, and the typical layout of a stand-alone PV system modeled using PVsyst software.

The configuration of the stand-alone PV system modeling is thoroughly addressed, followed by a visualization of the implemented APV design. The Land Equivalent Ratio (LER) benefits are calculated and briefly analyzed to demonstrate land-use efficiency. Additionally, a prototype for electrical shading analysis is presented, incorporating a block diagram and schematic circuit diagram for better understanding. Lastly, the chapter includes a detailed load calculation based on daily energy consumption, ensuring the design meets practical energy requirements.

4 Results Analysis and Discussion

This chapter provides the overall evaluation of results and their performance of Stand-alone APV system. Section 4.1 describes the Gardening plantation using Shade and without shade. However, total 8 crops are studied such as Tomato, Brinjal, Green chili, Lettuce, Cucumber, Aloevera, Snake-gourd, Rose flower. All those are analysed in terms of plant height, Number of leaves, number of flowers and fruits, size of fruits and weight of the shade and non-shaded crops are introduced. Then, discuss Performance Analysis of stand-alone APV model using PVsyst Software are discussed in Section 4.2. Electrical Shading Analysis are discussed in Section 4.3. Section 4.4 demonstrate the LER analysis of the proposed APV system. Finally, Section 4.5 includes the summary and concluding remarks of Chapter 4.

4.1 CROPS PLANTATION UNDER SOLAR SHADE AND WITHOUT SHADE

In this research project, a total of eight crops are studied, such as tomato, brinjal, green chili, lettuce, aloe vera, Cucumber, snake-gourd and rose flower both under solar shade and without shade. Three plants data are considered in each crop under shade and without shade. All these crops are analyzed in terms of the following parameters, where up to 11th week data are considered as represented in Table 4.1.

Table 4.1: Plant Measurement Parameter of the APV System

Shading Condition	Plant Parameter Considered				
Under Shade	Height	No. of leaves	No. of Flowers	No. of Fruits	Weight of Fruits
Without Shade	Height	No. of leaves	No. of Flowers	No. of Fruits	Weight of Fruits

4.1.1 Tomato Growth Under PV Panel Shade and Without Shade

Figure 4.1 illustrates the comparison between plants grown under Agrivoltaics (APV) shade and those grown without shade in terms of (a) height, (b) number of leaves, (c) number of flowers, and (d) number of fruits, all measured over 11 weeks where height and leaves measured in centimeters (cm).

a) Tomato Height Over the Weeks Under APV and Without Shade:

In Figure 4.1(a), tomato plants grown in APV shade develop steadily and consistently with fewer fluctuations, perhaps because of the regulated climatic circumstances that lessen stress from strong sunshine or temperature swings. Nevertheless, by the tenth week, the maximum height of these shaded plants had been marginally reduced. Conversely, plants growing in the absence of shade grow initially more quickly and taller, but their growth is more erratic, particularly in the later weeks, indicating that they are under more stress from the sun and other environmental conditions. In general, plants growing without shade grow initially more quickly and taller, but they also undergo more dramatic variations, suggesting possible stress. On the other hand, plants under shade develop more steadily, although more slowly, and at the end of the observation period, they have reached a smaller maximum height.

b) Number of Leaves Growth Over the Weeks Under APV and Without Shade:

Tomato plants in APV shade [Fig. 4.1(b)] show a progressive rise in leaf production that peaks between the 7th to 9th weeks. The moderated environmental conditions allow for a longer duration of leaf retention. Non-shaded plants, on the other hand, exhibit a quicker rate of leaf growth, peaking earlier but also going through a more abrupt drop, probably as a result of stress from the intense sunshine. According to this comparison, plants that are not shaded tend to focus more on quick development but also experience faster leaf drop, whereas plants that are shaded maintain more resilience and health through continuous leaf creation.

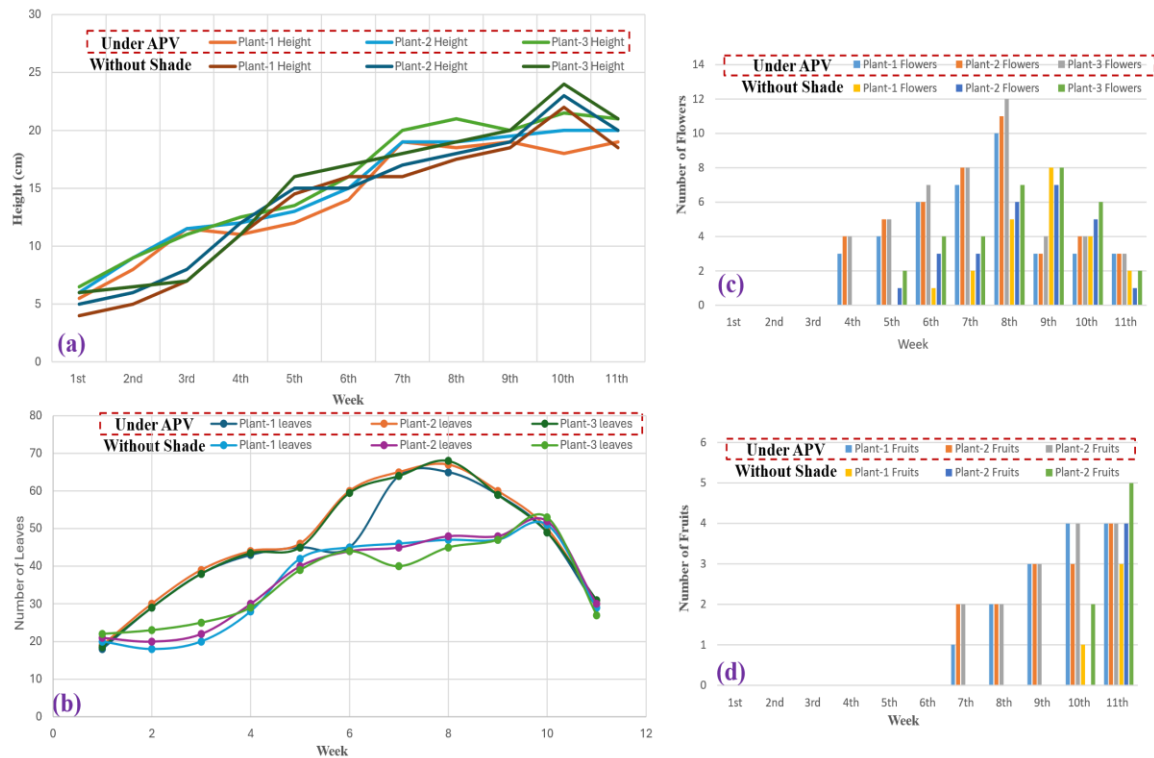


Fig. 4.1. Tomato growth under solar shade and without solar shade (a) height, (b) leaf, (c) flower, and (d) fruit.

c) Number of Flowers Over the Weeks Under APV and Without Shade:

The bar chart of Figure 4.1(c) shows the weekly blossom production of tomato plants planted in APV shadow compared to those grown in sunlight. Plants grown under APV shade flower earlier (during the 4th week) and more reliably. Growing till the eighth week of flowering. Conversely, non-shaded plants peak in the eighth and ninth weeks and blossom later and more heavily. But then they quickly disappear, suggesting a shorter but more intense flowering phase brought on by greater light. Unshaded plants typically flower for shorter periods of time and with greater unpredictability, while shaded plants flower for longer periods of time but with less quantity.

d) Number of Fruits Growth Over the Weeks Under APV and Without Shade:

Shaded tomatoes, as shown in Figure 4.1(d), begin bearing fruit earlier, with a significant increase in fruit quantity between weeks seven and ten. This suggests that the plants are benefiting from moderated light levels, resulting in a stronger

and earlier fruiting response. In contrast, non-shaded plants begin fruiting later, starting in the tenth week and peaking in the eleventh. Overall, shade-grown tomatoes achieve similar fruit quantities earlier due to their accelerated growth and earlier flowering.

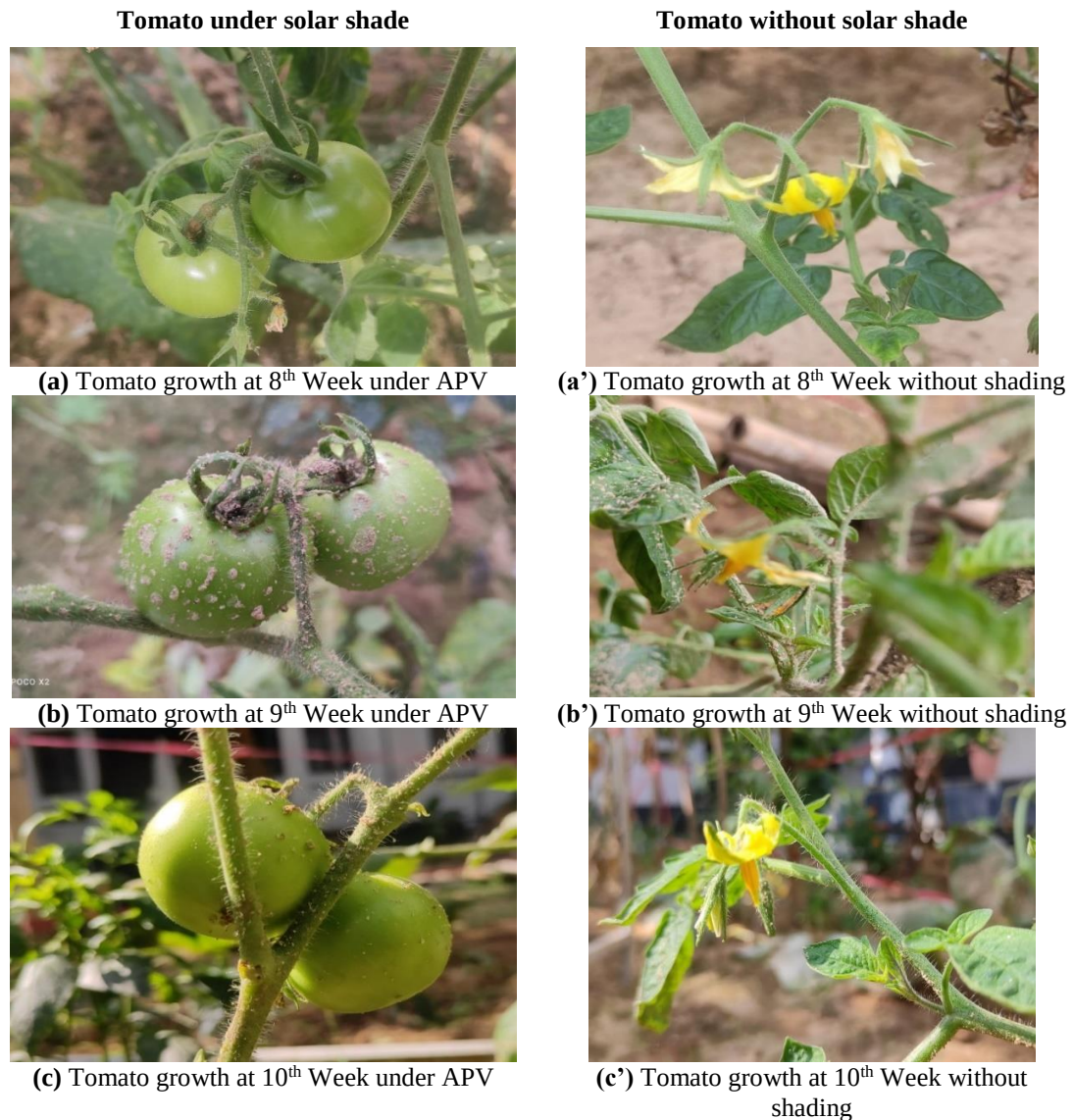


Fig. 4.2: Tomato growth under APV and without shading.

Figure 4.2 illustrates tomato growth under Agrivoltaics (APV) systems and without shading. The yields of tomato plants are 0.7 kg in the APV system compared to 1.75 kg without photovoltaic (PV) shading. Additionally, the electricity yield from the APV system is 1.157 kWh, while electricity production without APV is 1.96 kWh. Using equation (3.1), the land equivalent ratio for tomatoes is calculated to be 1. Based on the data for plant height, number of

leaves, number of fruits, and fruit weight, tomato growth under the APV system is approximately equivalent to that without shading. Therefore, **the tomato does not show yield advantage in the APV system.**

4.1.2 Brinjal Growth Under PV Panel Shade and Without Shade

Figure 4.3 illustrates the comparison between Brinjal growth under Agrivoltaics (APV) shade and those grown without shade in terms of (a) height, (b) number of leaves, (c) number of flowers, and (d) number of fruits, all measured over 11 weeks where height and leaves measured in centimeters (cm).

a) Brinjal Height Under APV Shade and Without Shade:

Figure 4.3 (a) represents the height progression of plants cultivated under Agrivoltaics (APV) shade over an 11-week period, compared to those grown without shade. Throughout the observation period, plants under APV shade demonstrate a stable and consistent growth pattern with fewer fluctuations, indicating that shading contributes to more uniform growth by mitigating the impact of environmental stressors such as intense sunlight and temperature variations. Maximum height is observed in 8th week after that suddenly it is declined. In contrast, non-shaded plants exhibit a more rapid initial growth but with greater variability, achieving a slightly higher maximum height by the eleventh week. However, this rapid growth is accompanied by significant fluctuations, likely due to increased exposure to environmental stressors like elevated temperatures and potential water stress, which may compromise the stability of their growth.

(b) Number of Leaves Under APV Shade and Without Shade:

The quantity of leaves produced over an 11-week period by plants grown in APV shade versus those grown in the absence of shade is shown in Figure 4.3(b). When grown in under APV, brinjal produces more leaves gradually and steadily, reaching a peak in the ninth and tenth week. This pattern indicates that, maybe

as a result of less stress and more stable conditions, the shaded habitat permits a more constant and prolonged leaf production phase. On the other hand, non-shaded plants, however, the number of leaves starts to increase more slowly after reaching their peak. This suggests that although these plants grow leaves more rapidly, possibly in reaction to stress factors like intense sunlight or temperature variations. Overall, the tendency indicates that while non-shaded conditions may result in faster but less stable leaf creation, shading encourages more prolonged and stable leaf growth.

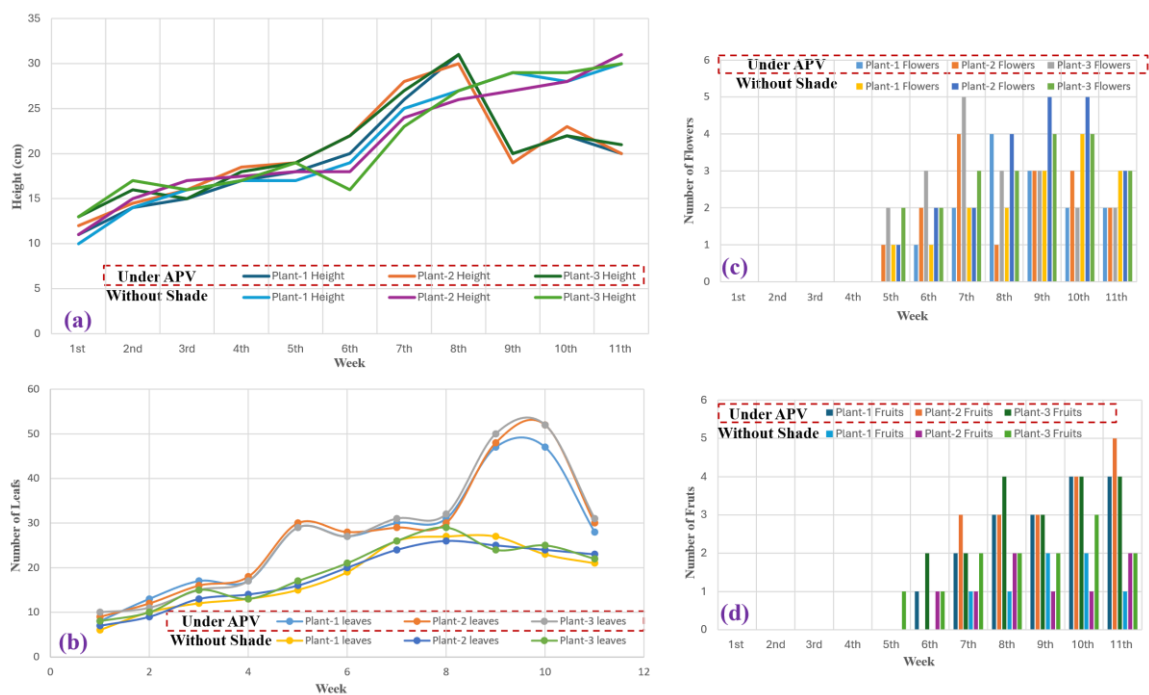


Fig. 4.3: Brinjal growth under solar shade and without shade (a) height, (b) leaf, (c) flower, and (d) fruit.

(c) Number of Flowers Under APV Shade and Without Shade:

Bar chart of Figure 4.3(c) compares the number of blooms produced by brinjal plants cultivated under APV shade with those grown without shade over an 11-week period. Brinjal plants under APV shade display a delayed onset of flowering and produce fewer overall blooms compared to their non-shaded counterparts. Flowering under shaded conditions is more spread out over time, suggesting a longer but less intense flowering period. This indicates that the APV

shade may slow down the blooming process, leading to fewer flowers overall but potentially extending the flowering duration due to reduced light availability. In contrast, non-shaded plants begin flowering earlier and produce more blooms during their peak weeks, particularly in the 9th and 10th weeks. However, this flowering period is shorter and more intense, with a rapid decline following the peak. The comparison highlights that while non-shaded conditions promote earlier and more abundant flowering, they may also accelerate resource depletion, resulting in a shorter overall flowering period.

d) Number of Fruits Under APV Shade and Without Shade:

The number of fruits that the Brinjal plants produced over an 11-week period both under and without Agrivoltaics (APV) shade is shown in Figure 4.3(d). The plants consistently produce more fruit under APV shade; this is especially evident starting in the 7th week, when the largest number of fruits are recorded by the 11th week. This pattern implies that the APV shade's-controlled lighting settings foster the best conditions for fruit development, perhaps by lessening heat stress and enhancing water evaporation, which encourages steady growth and fruiting. On the other hand, the fruit production pattern of the plants without shade is more irregular, resulting in a lower total number of fruits produced. The variations in fruit production uniformity and quantity may be caused by environmental stresses including increased temperatures and increased water loss, which can be brought on by direct solar exposure. Overall, the findings show that by creating a more stable growing environment, APV shading enhances the production of Brinjal fruit.

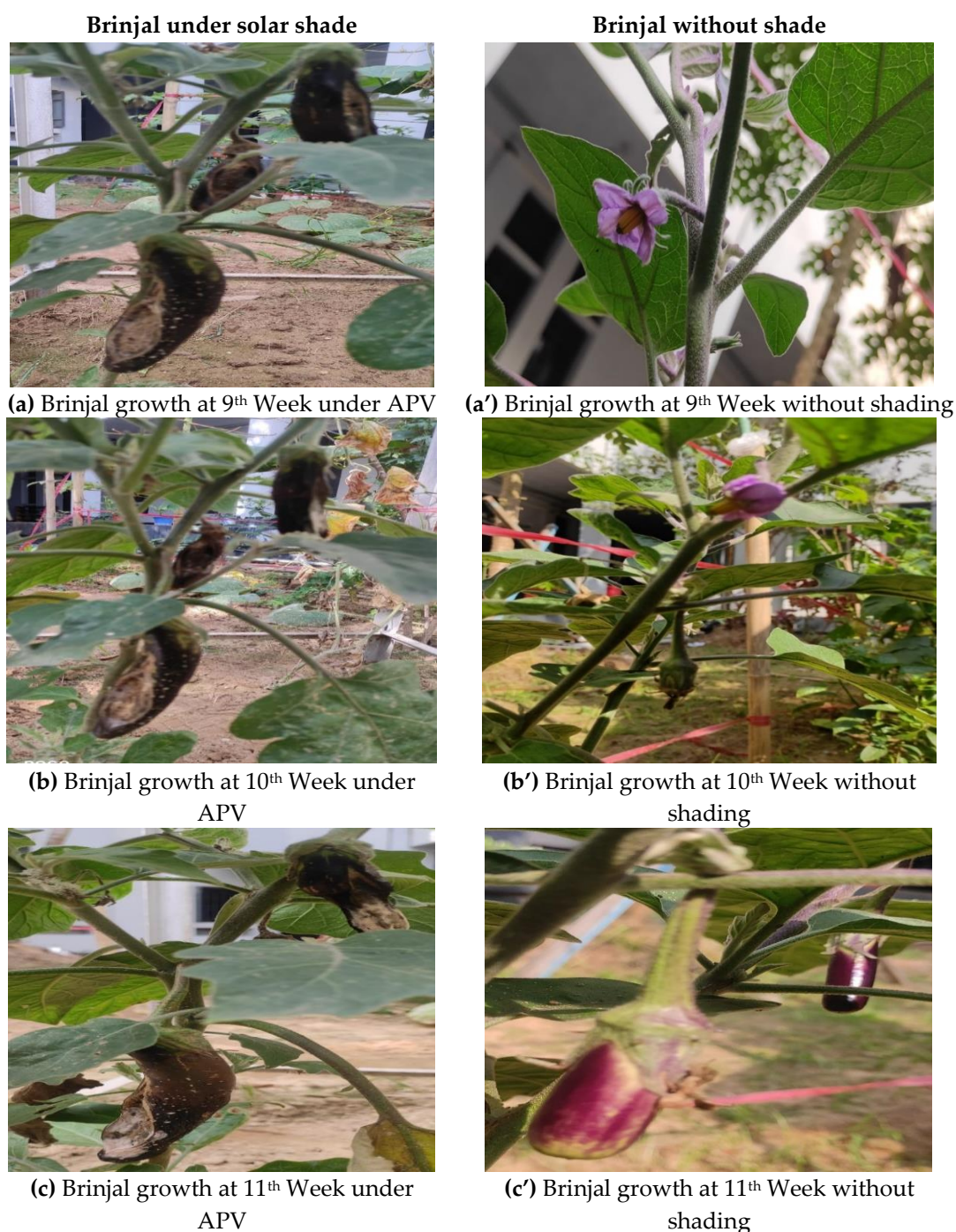


Fig. 4.4. Brinjal growth under APV and without shading.

Brinjal growth under APV systems and without shading effects is illustrated in Figure 4.4. The yields of brinjal plants are 2 kg in the APV system compared to 1.5 kg without photovoltaic (PV) shading. Additionally, the electricity yield from the APV system is 1.157 kWh, whereas electricity production without APV reaches 1.96 kWh [64]. By applying eq (3.1), the land equivalent ratio for brinjal is calculated to be 1.93. In summary, based on the data for plant height, number

of leaves, number of fruits, and fruit weight, brinjal growth is more favorable under the APV system compared to without shade. **Therefore, cultivating brinjal in an APV system is advantageous contest to Bangladeshi climate.**

4.1.3 Green Chili Growth Under PV Panel Shade and Without Shade

Figure 4.5 illustrates the comparison between green chili growth under Agrivoltaics (APV) shade and those grown without shade in terms of (a) height, (b) number of leaves, (c) number of flowers, and (d) number of fruits, all measured over 11 weeks where height and leaves measured in centimeters (cm).

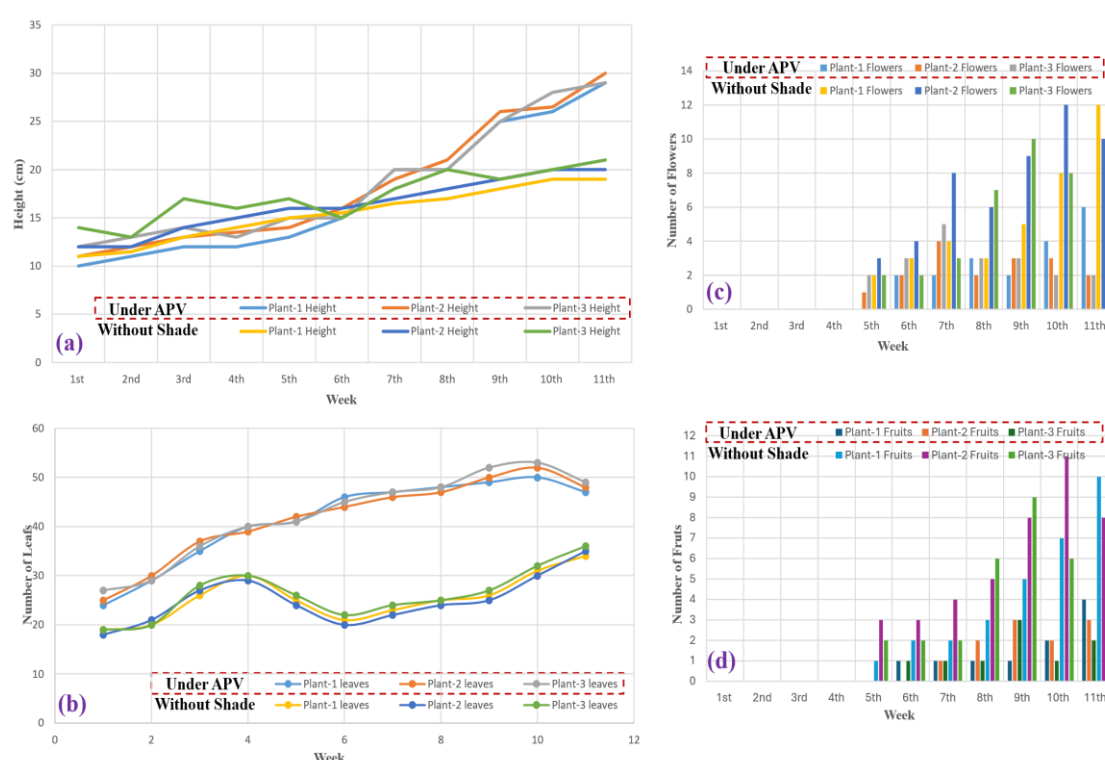


Fig. 4.5: Green Chili growth under solar shade and without solar shade (a) height, (b) leaf, (c) flower, and (d) fruit.

(a) Height of Green Chili Plants Under APV Shade and Without Shade:

The height growth of green chili plants grown in APV shade during an 11-week period is compared to those grown in the absence of shade in Graph 4.5(a). The plants cultivated in APV shadow show a steadier and even growth in height, suggesting that the shade provides a more stable growth environment. After 8th week, the shaded plants usually attain a little smaller maximum height than the

unshaded plants, where maximum height is found approximately 29 cm. The plants without shade grow constant increasing but height is lower than under APV, indicating that they are more vulnerable to environmental stressors, such as strong sunshine or harsh temperatures, which results in less consistent development patterns overall.

(b) Number of Leaves (Green Chili) Under APV Shade and Without Shade:

The number of leaves generated by green chili plants in APV shade over an 11-week period is compared with those without shade in graph 4.5(b). According to the findings, green chili grown in shade likely to have a longer-lasting rise in leaf production, which peaks around week ten. This shows that a more-steady output may be possible by extending the time of leaf growth and reducing stress due to the shadowing impact. On the other hand, compared to APV shade, green chili grows less quickly in the without shade. Maximum is leaves is found in eleventh week which is roughly 35.

(c) Number of Flowers Under APV Shade and Without Shade:

Graph 4.5(c) demonstrates that flower production under APV shade remained relatively steady, with gradual growth beginning in the fifth week and becoming more pronounced by the seventh week. In contrast, plants without shade exhibited a more erratic flower production pattern, with a significant increase starting in the eighth week. By the eleventh week, green chili plants grown without APV shade generally produced slightly more flowers than those grown under shade, suggesting that the absence of shade may have positively influenced flower development in the green chili plants.

(d) Number of Fruits Growth Under APV Shade and Without Shade:

The fruit production with and without APV shade in the fourth graph, 4.5(d), displays a tendency that is more diverse. In all circumstances, fruit began to appear by the fifth week; however, the fruit output of the shaded plants increased gradually, peaking between the ninth and eleventh week. When compared to the

green chili under APV shade, the green chili without shade showed a more consistent fruiting pattern, especially starting in the eighth week. While plants without shade seemed to reach peak fruiting slightly earlier, there was a difference in the number of fruits produced by both conditions by the eleventh week. This suggests that the absence of shade may have led to a more stable and maybe quicker fruit development in green chili plants.



Fig. 4.6. Green Chili growth under APV and without shading.

Figure 4.6 shows the growth of green chili plants under APV and without shading. In the APV system, the green chili yield is 0.44 kg, whereas without PV shading, the yield is 0.11 kg. Additionally, the electricity yields in the APV and non-PV systems are 1.157 kWh and 1.96 kWh, respectively. Using eq (3.1), the land equivalent ratio for green chili is calculated to be 0.96. Based on the data for plant height, number of leaves, and number of fruits, the growth of green chili is more favorable in non-shaded conditions compared to the APV system. **Therefore, green chili cultivation is disadvantageous under the APV system.**

4.1.4 Lettuce Growth Under PV Panel Shade and Without Shade

Figure 4.7 illustrates the comparison between lettuce growth under Agrivoltaics (APV) shade and those grown without shade in terms of (a) height, (b) number of leaves, all measured over 11 weeks where height and leaves measured in centimeters (cm).

a) Height of Lettuce Plant Under APV Shade and Without Shade:

The height growth of lettuce plants cultivated under APV shade during an 11-week period is compared to those grown without shade in Figure 4.7(a). According to the findings, plants growing in APV shade typically demonstrate a more progressive and consistent increase in height throughout the course of the observation period. This implies that the APV system's shading aids in reducing the effects of environmental stresses like strong sunshine and high temperatures, promoting a more-steady development pattern. On the other hand, lettuce planted in full sun grows slowly; height is increased up to 4th week after that it is declined. However, after 7th week it is continually increasing. Compared to non-shaded lettuce, plants grown under shade demonstrate greater growth and exhibit more consistent development by the end of the observation period.

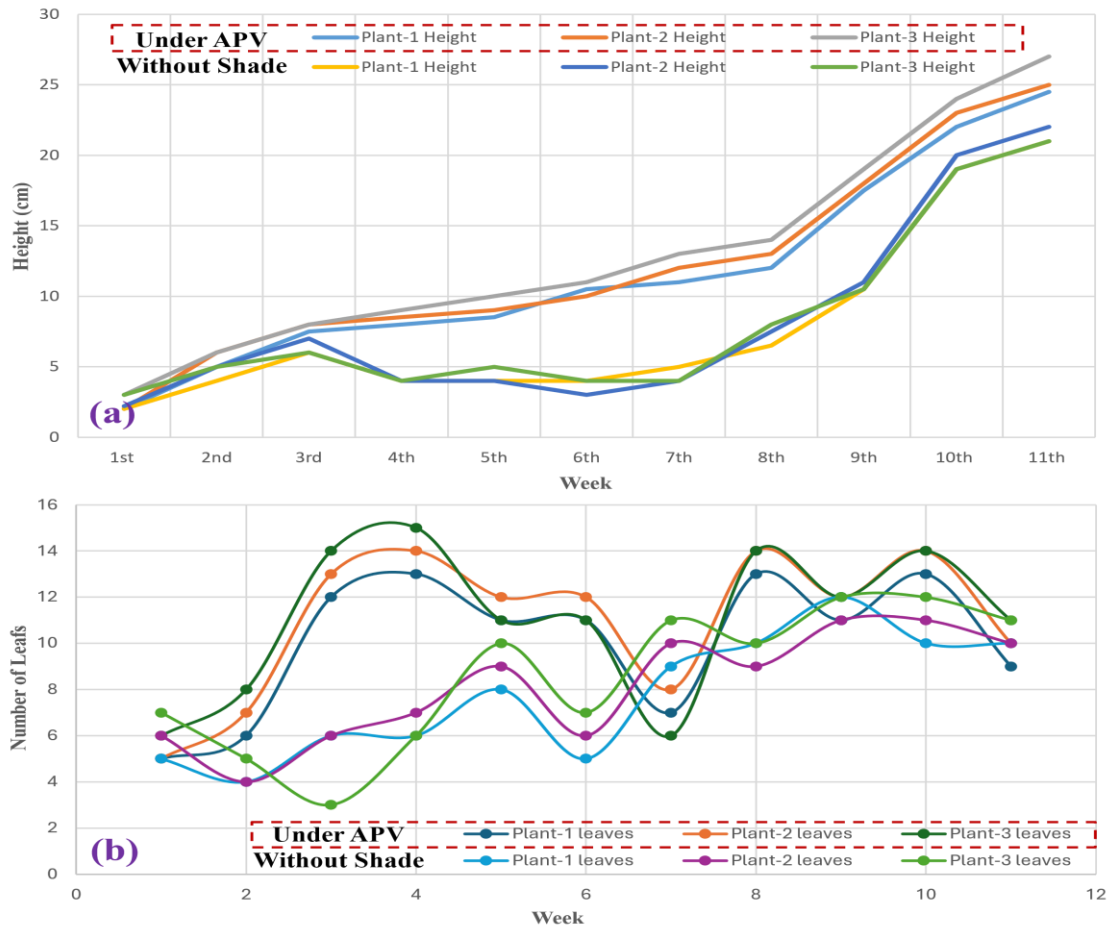


Fig. 4.7: Lettuce growth under solar shade and without solar shade (a) height, and (b) leaf.

b) Number of Lettuce Leaves Growth Under APV Shade and Without Shade:

A comparison of the number of leaves generated over an 11-week period by lettuce plants grown in APV shade against those grown in the absence of shade is shown in Figure 4.7(b). According to the statistics, leaf production is more consistent when grown in APV shadow; leaves steadily increase until approximately the fourth week, at which point they start to decline. On the other hand, lettuce cultivated without shade demonstrates more noticeable variations in leaf output, which peaks approximately one week into the growing season and then shows considerable variability. For non-shaded lettuce, the data indicate a steady rise in the number of leaves, peaking in the tenth week. Both shade- and non-shaded plants reach a stable condition after the eighth week. In general, the

graph shows that lettuce grown in APV shade yields more leaves production than lettuce cultivated in the without shade.

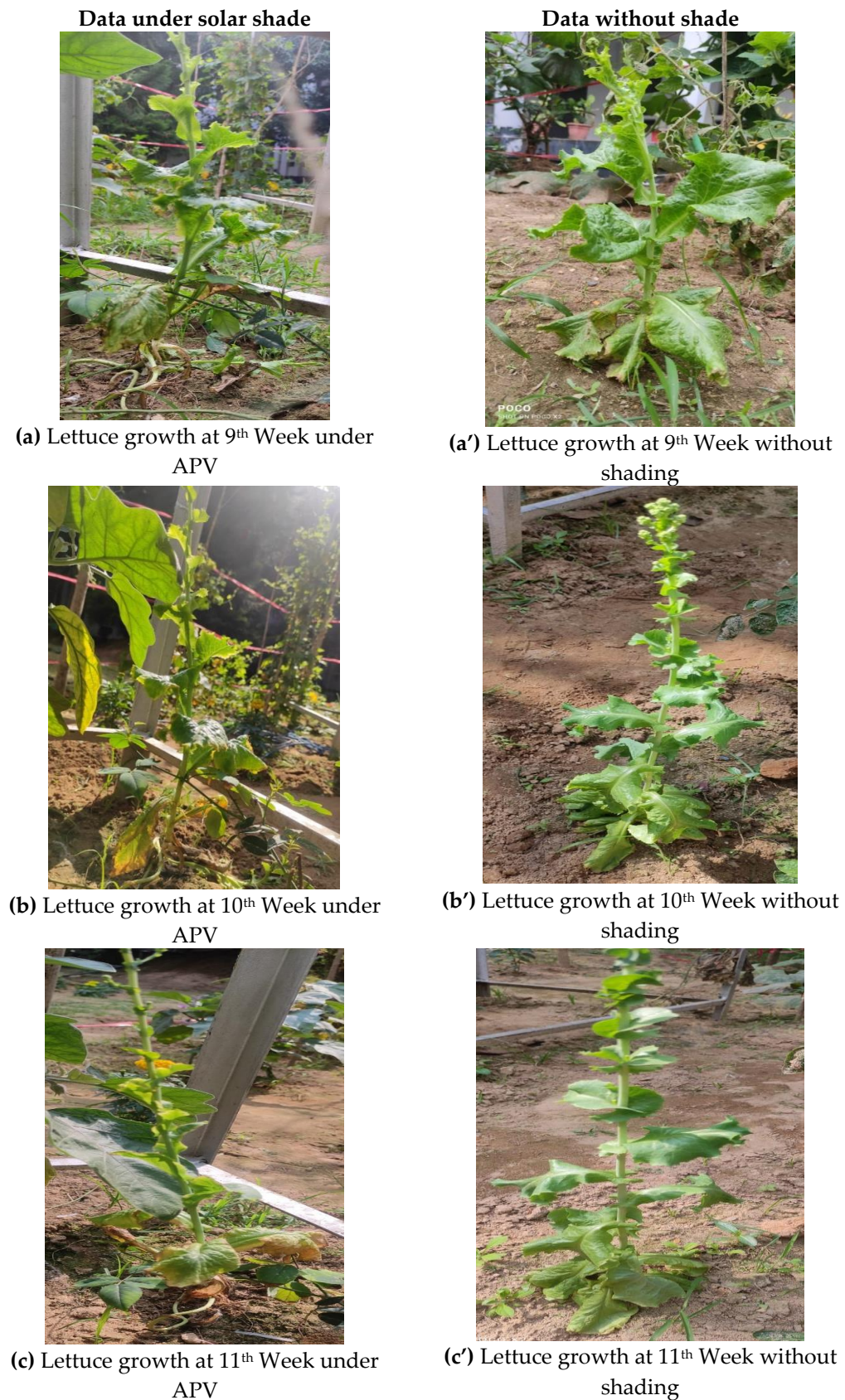


Fig. 4.8. Lettuce growth under APV and without shading.

Figure 4.8 presents the growth comparison of lettuce cultivated under an Agrivoltaics (APV) system and without shading. The lettuce yield in the APV system is 0.5 kg, slightly higher than the 0.45 kg yield in the non-shaded system. In terms of electricity production, the APV system generates 1.157 kWh, whereas the system without solar shading produces 1.96 kWh [64]. Using Equation (3.1), the land equivalent ratio (LER) for lettuce is determined to be 1.85. These calculations indicate that growing lettuce under the APV system is substantially more profitable compared to the non-shaded system, **making the APV system a more advantageous method for lettuce cultivation.**

4.1.5 Alo vera Growth Under PV Panel Shade and Without Shading

Figure 4.9 presents a comparison of aloe vera growth under Agrivoltaics (APV) shade and without shade, focusing on (a) height and (b) the number of leaves, all measured in centimeters (cm) over an 11-week period. The height of aloe vera plants grown in APV shade is increasing steadily, with minor variations around the 4th and 7th weeks, but overall, a constant growth pattern is seen. Conversely, plants produced in full sun grow smaller than those planted in APV shade, indicating more erratic development patterns. This shows that aloe vera grows more when exposed to shade because less intense sunlight causes heat stress, which stabilizes photosynthetic activity and reduces transpiration-related water loss. The plants can focus more of their energy on growth rather than stress reactions in this regulated shaded environment, which leads to increased overall development.

The quantity of leaves that aloe vera plants generate in both scenarios is shown in Graph 4.9(b). Under APV shade, plants show a consistent rise in leaf production, particularly after the sixth week, reaching a greater leaf count by the eleventh week. On the other hand, plants grown in full sun also show an increase in the number of leaves, but their growth is less steady and there is some stalling between the fourth and seventh week. This indicates that although while both

plant groups eventually generate different amounts of leaves, the APV system's shading promotes more leaf production and more steady development over time, probably because it lessens the stress caused by external variables like strong sunshine.

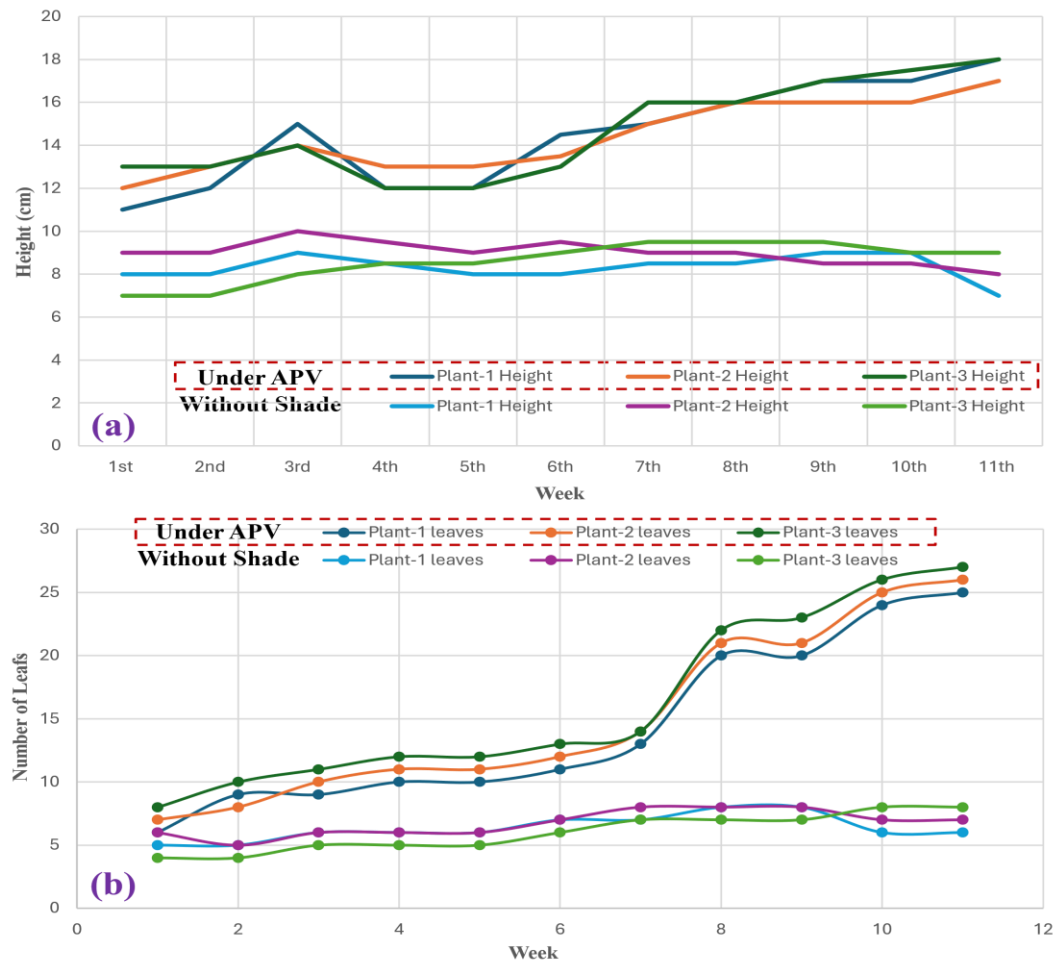


Fig. 4.9: Aloe Vera growth under solar shade and without solar shade (a) height, and (b) leaf.

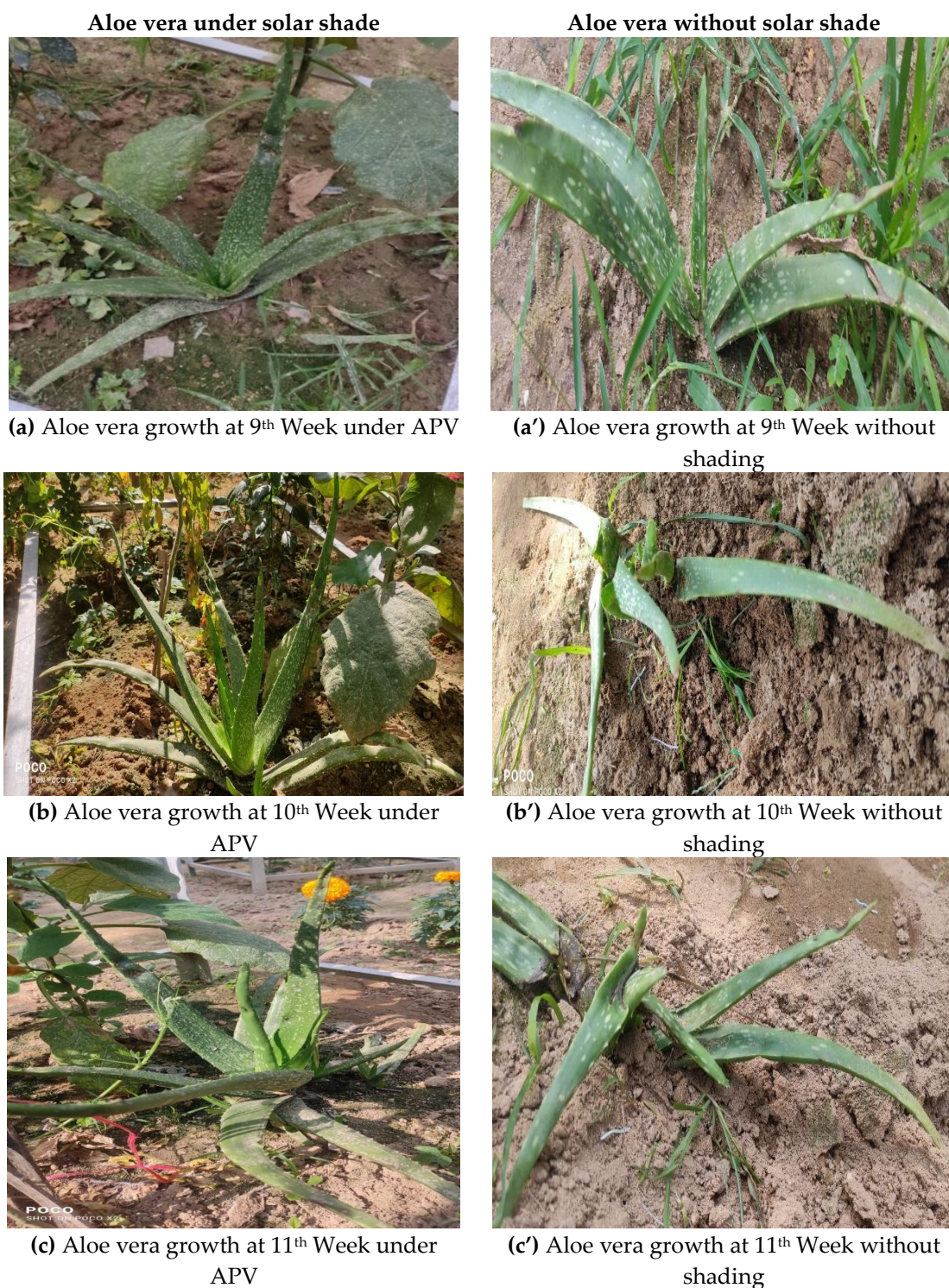


Fig. 4.10. Alovera growth under APV and without shading.

Figure 4.10 depicts the growth of aloe vera under APV and without shading. The yields of aloe vera in the APV and non-APV systems are 1.9 kg and 1.5 kg, respectively. Additionally, the electricity yield in the APV system is 1.157 kWh, whereas it is 1.96 kWh without APV. Using eq (3.1), the land equivalent ratio for aloe vera is calculated to be 1.86. Therefore, aloe vera growth is more favorable

under the APV system compared to without solar shading, **making aloe vera cultivation advantageous in an APV system.**

4.1.6 Cucumber Growth Under PV Panel Shade and Without Shade

From Figure 4.11, compare the growth, flowering, and fruiting performance of cucumber plants grown under **APV** and **without shade** conditions over 11 weeks. Plants under APV show slightly grteater performance in all aspects compared to those without shade. In terms of height and leaf production, both conditions follow similar growth patterns, but plants without shade achieve marginally greater heights and more leaves, particularly after the 8th week. Flowering and fruiting also peak around the same time (7th–9th weeks) for both conditions, but plants without shade consistently produce slightly more flowers and fruits. These differences suggest that shading under APV slightly limits light availability, impacting overall plant growth and yield, though plants under APV still perform reasonably well.

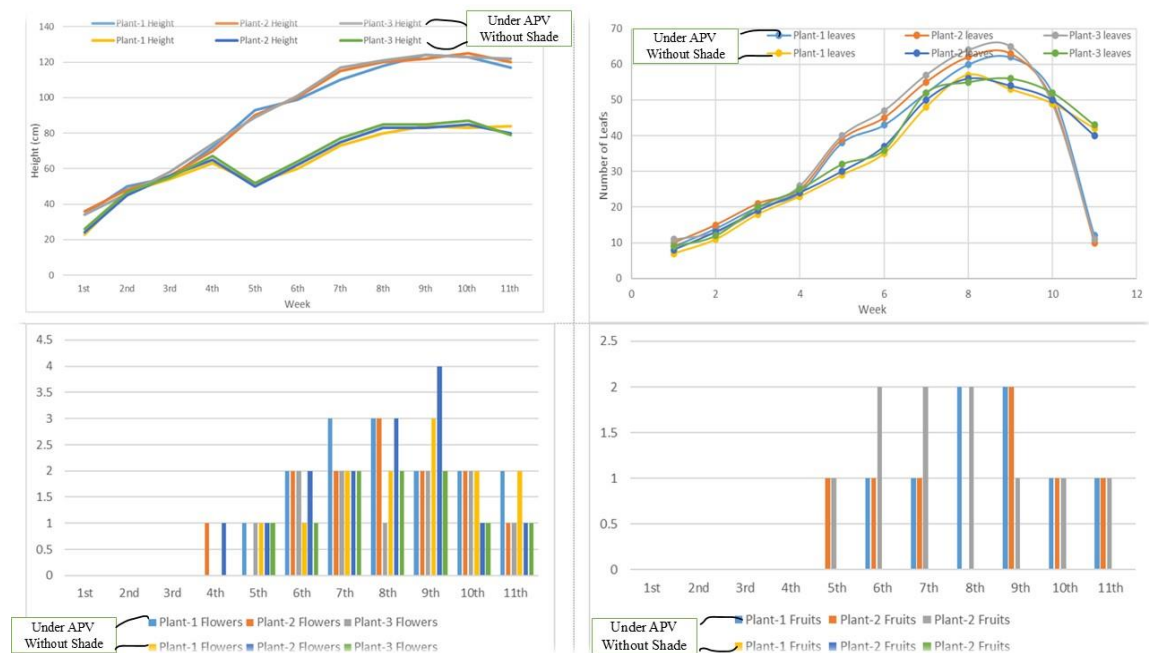


Fig. 4.11: Cucumber growth under solar shade and without solar shade (a) height, and (b) leaf, c) Flowers, d) Fruits

Cucumber under solar shade	Cucumber without shade
 (a) Cucumber growth at 10th Week under APV	 (a') Cucumber growth at 10th Week without shading
 (b) Cucumber growth at 11th Week under APV	 (b') Cucumber growth at 11th Week without shading

Fig. 4.12: Cucumber growth under APV and without shading.

Cucumber growth under APV systems and without shading effects is illustrated in Figure 4.12. 0.6 kg of Cucumber is found in the APV system, whereas without PV yield is 1.15 kg. Additionally, the electricity yield from the APV system is 1.157 kWh, whereas electricity production without APV reaches 1.96 kWh. By applying eq (3.1), the land equivalent ratio for cucumber is calculated to be 2.1. In summary, based on the data for plant height, number of leaves, number of fruits, and fruit weight, cucumber growth is more favorable under the APV system compared to without shade. **Therefore, cultivating cucumber in an APV system is advantageous.**

4.1.7 Snake-Gourd Growth Under PV Panel Shade and Without Shade

Figure 4.13, present a comparative analysis of snake gourd growth, flowering, and fruiting under two conditions: **Under APV** and **Without Shade**. Plants without shade demonstrate superior performance across all parameters. In terms of height, plants without shade show consistent growth, reaching significantly greater heights compared to those under APV. Leaf production follows a similar trend for both conditions, peaking around the 9th–10th week, with plants without shade exhibiting a slightly higher leaf count. Flowering and fruiting are more pronounced in plants without shade, particularly between the 8th and 10th weeks, where the number of flowers and fruits is notably higher. These findings suggest that shading under APV moderately limits light availability, impacting growth and yield, though plants without shade still maintain higher productivity.

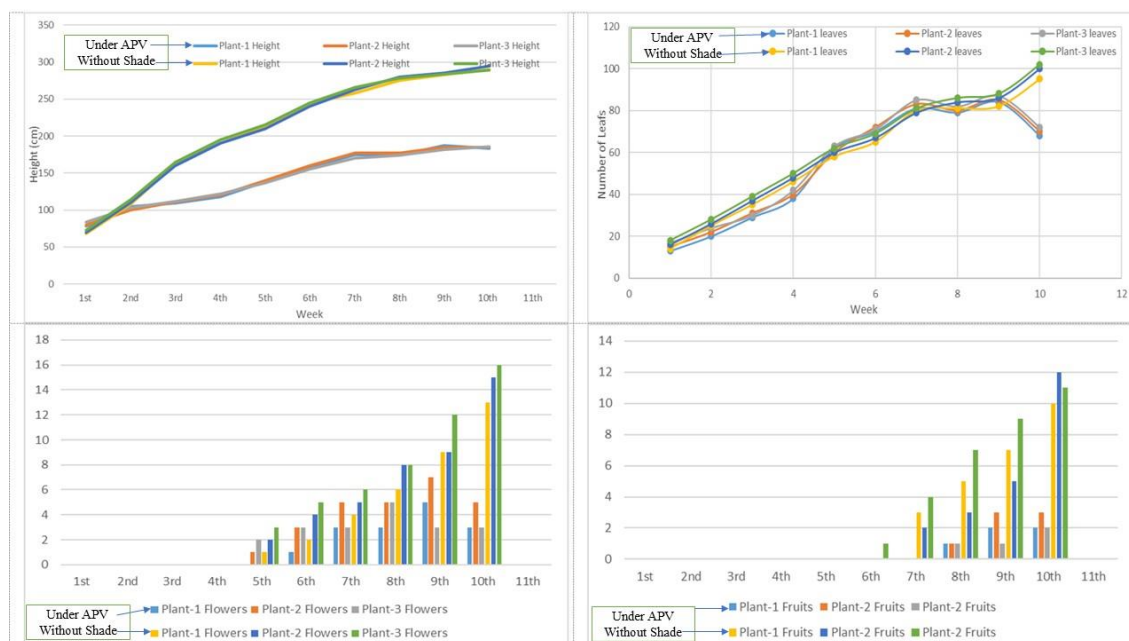
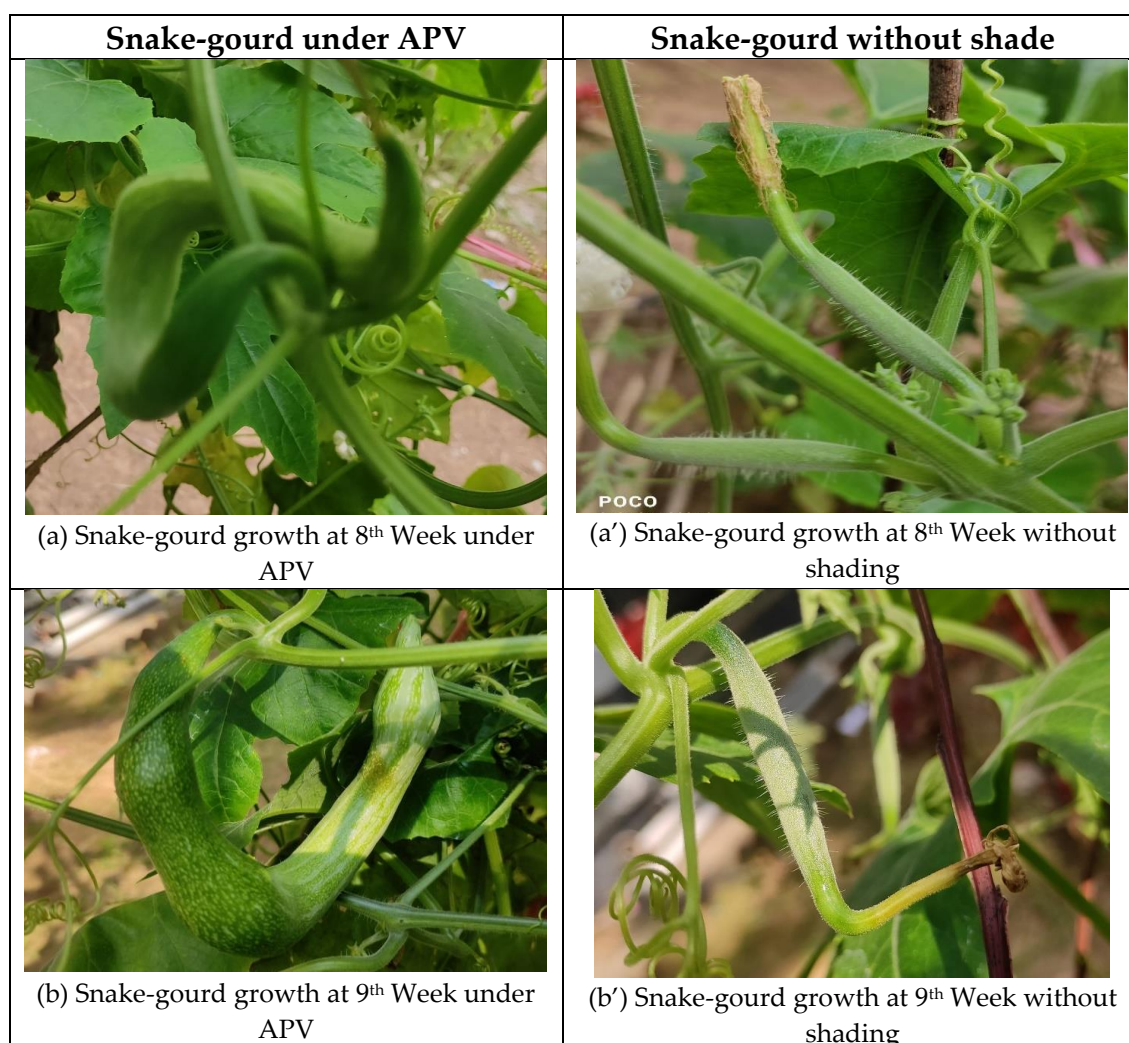


Fig. 4.13: Snake gourd growth under solar shade and without solar shade (a) height, (b) leaf, c) Flowers, and d) Fruits.



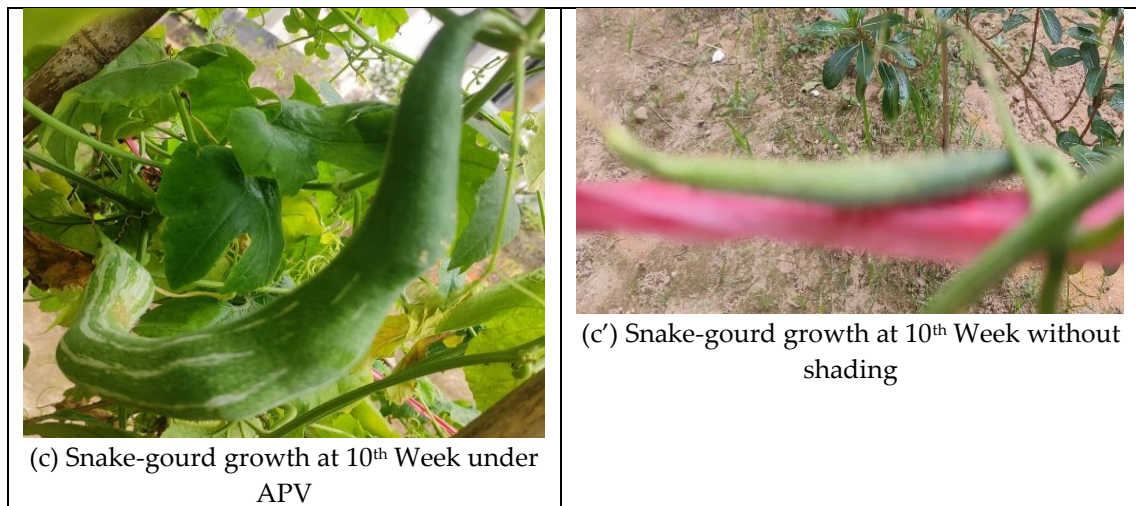


Fig. 4.14: Snake-gourd growth under APV and without shading.

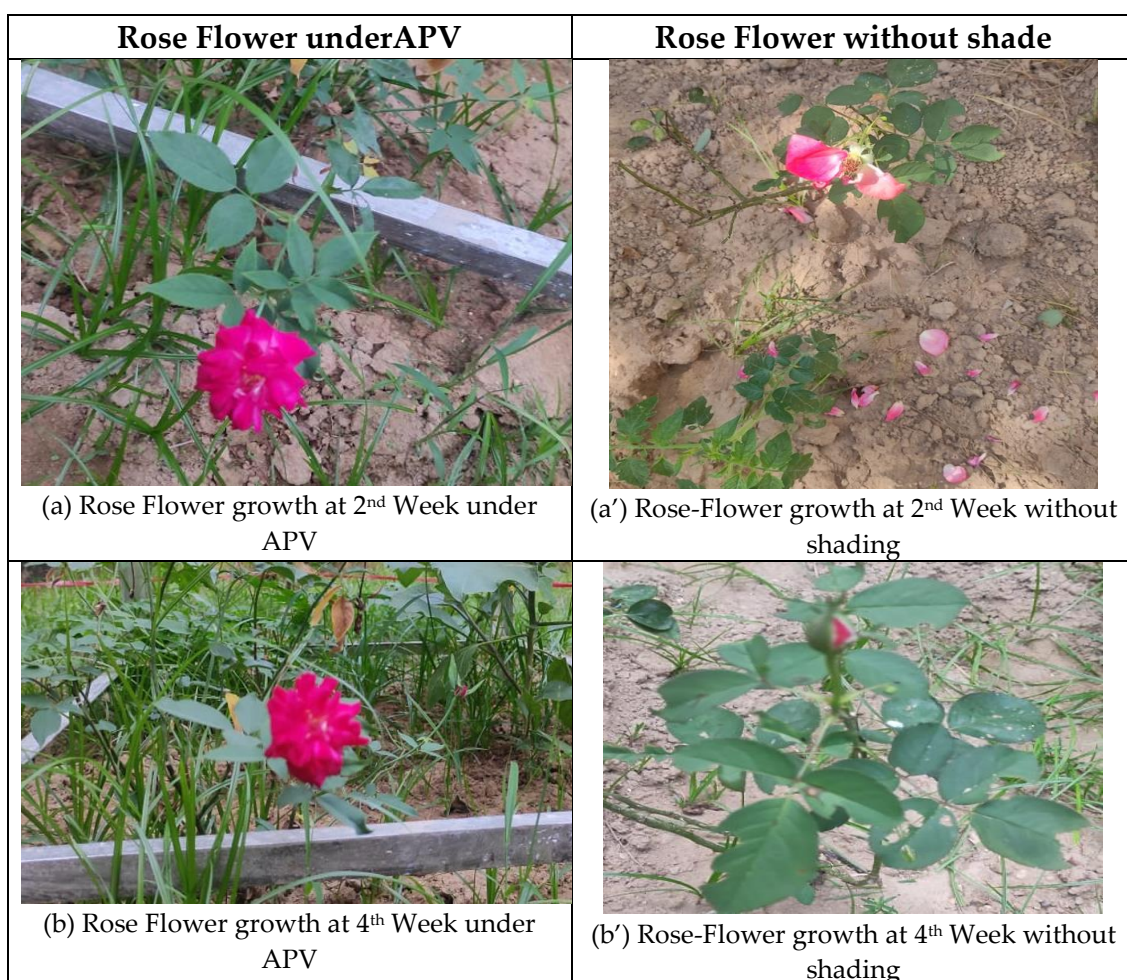
Figure 4.14 shows the growth of snake-gourd plants under APV and without shading. In the APV system, the snake-gourd yield is 1 kg of snake-gourd is found in the APV system, whereas without PV yield is 3 kg. Additionally, the electricity yields in the APV and non-PV systems are 1.157 kWh and 1.96 kWh [64], respectively. Using eq (3.1), the land equivalent ratio for snake-gourd is calculated to be 0.93. Based on the data for plant height, number of leaves, and number of fruits, the growth of snake-gourd is more favorable in non-shaded conditions compared to the APV system. **Therefore, snake-gourd cultivation is disadvantageous under the APV system.**

4.1.8 Rose Flower Growth Under PV Panel Shade and Without Shade

From Figure 4.15, The graphs analyse the growth, leaf production, and flowering trends of **rose flower** grown under two conditions: **Under APV** and **Without Shade**. In terms of height, rose plants without shade grow consistently taller, while those under APV display moderate growth likely due to reduced light availability. However, Leaf production follows greater production in case of APV, peaking around the 4th week. Flowering begins around the 4th week and peaks between the 7th and 8th weeks, with plants under APV producing a greater number of flowers. These results suggest that shading under APV impacts light penetration, reducing growth and flowering in rose plants, though their productivity remains reasonable under APV conditions.



Fig. 4.15: Rose Flower growth under solar shade and without solar shade (a) height, (b) leaf, and c) No. of Flowers.



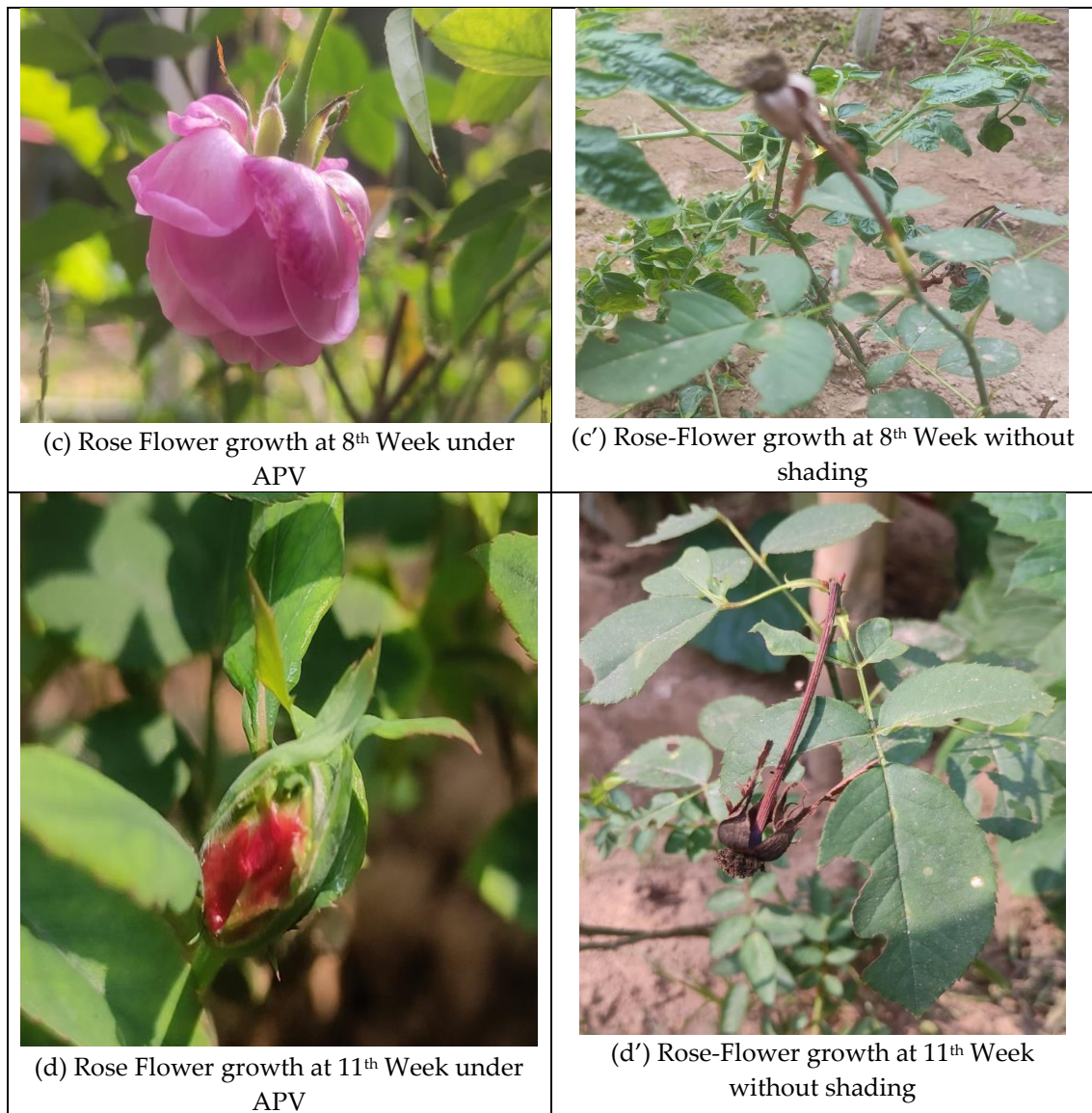


Fig. 4.16: Rose Flower growth under APV and without shading.

Figure 4.16 presents the growth comparison of rose flower cultivated under an Agrivoltaics (APV) system and without shading. Yield of plants in APV and without PV are 2 piece and 1 piece found in 11th week respectively. In terms of electricity production, the APV system generates 1.157 kWh, whereas the system without solar shading produces 1.96 kWh. Using Equation (3.1), the land equivalent ratio (LER) for rose flower is determined to be 2.6. These calculations indicate that growing rose flower under the APV system is substantially more profitable compared to the non-shaded system, **making the APV system a more advantageous method for rose flower cultivation.**

4.2 PERFORMANCE ANALYSIS OF SAPV MODEL

Table 4.2 provides summarizes the monthly performance of a 300-watt Agrivoltaic (APV) system, highlighting key energy parameters. The GlobHor and GlobEff columns indicate the global horizontal and effective irradiance received, showing higher values during summer months like March to June. E_Avail represents the available energy from the system, peaking at 40.02 kWh in March. E_Unused and E_Miss show energy losses, with E_Unused minimal in most months and E_Miss relatively higher during low irradiance months such as July and August. The E_User column reflects energy consumed, which remains consistent across months, averaging 32-34 kWh. Similarly, E_Load values represent the load requirement, which is steady at around 35.53 kWh. The SolFrac ratio demonstrates the solar fraction, indicating the system's ability to meet energy demand; it varies slightly, with values above 0.9 for most months, indicating high reliability. Annually, the system delivers 424.98 kWh of energy, with 382.36 kWh utilized by the user. The table provides critical insights into the efficiency and performance of the APV system across different seasons.

Table 4.2: Performance Analysis of SAPV model

300 Watt APV system Balances and main results								
	GlobHor kWh/m ²	GlobEff kWh/m ²	E_Avail kWh	EUnused kWh	E_Miss kWh	E_User kWh	E_Load kWh	SolFrac ratio
January	111.8	138.6	36.42	3.477	3.055	32.47	35.53	0.914
February	119.3	136.1	35.44	2.866	1.353	30.73	32.09	0.958
March	149.4	155.8	40.02	6.134	2.288	33.24	35.53	0.936
April	161.2	154.6	39.65	4.202	0.028	34.35	34.38	0.999
May	159.2	142.6	36.69	1.114	1.129	34.40	35.53	0.968
June	129.6	113.4	29.26	0.255	5.527	28.85	34.38	0.839
July	128.9	113.6	29.38	0.000	7.285	28.24	35.53	0.795
August	134.3	125.6	32.02	3.351	7.797	27.73	35.53	0.781
September	134.2	133.2	34.32	2.201	2.740	31.64	34.38	0.920
October	129.3	142.2	36.45	3.023	3.416	32.11	35.53	0.904
November	120.8	147.3	38.24	2.711	0.299	34.08	34.38	0.991
December	111.3	140.9	37.09	1.693	1.013	34.51	35.53	0.972
Year	1589.3	1643.8	424.98	31.027	35.931	382.36	418.29	0.914

4.2.1 Performance Ratio (PR) and Solar Fraction (SF) Analysis

Figure 4.17 illustrates the monthly Performance Ratio (PR) and Solar Fraction (SF) for a 300-watt Agro-Photovoltaic (APV) system.

The performance ratio is the ratio of the PV system's actual yield (Y_f) to its reference yield (Y_r), which is calculated by eq (4.1), where PR indicates the performance Ratio, Y_f indicates the actual yield, and Y_r Indicates the reference yield. The Performance Ratio (PR), shown in red, represents the efficiency of the solar system, with values ranging between approximately 0.75 and 0.80 throughout the year. A slight dip is observed in the summer months (June and July), likely due to higher temperatures or shading effects reducing PV efficiency. This high PR reflects excellent system performance and efficiency.

$$PR = \frac{Y_f}{Y_r} \quad (4.1)$$

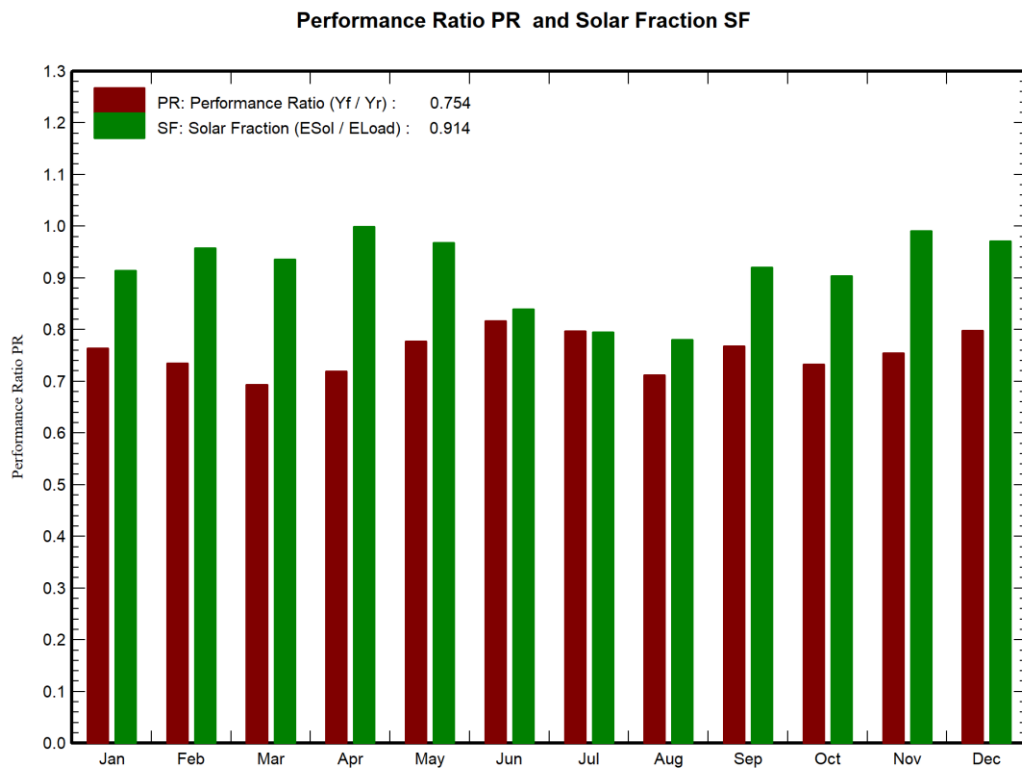


Fig. 4.17: Performance Ratio of the proposed SAPV System.

The Solar Fraction (SF), depicted in green, shows the proportion of the energy demand met by the PV system. The SF remains consistently high across the year,

ranging from around 0.78 in the summer to above 0.90 in most other months. Peaks in SF are visible in the spring (April-May) and fall (September-October), indicating optimal system performance under moderate sunlight and temperature conditions. Overall, the system demonstrates reliable year-round energy contribution with a high solar fraction and stable performance ratio, making it suitable for agricultural and energy generation integration.

4.2.2 Normalized Production and Loss Factor of 300 Wp SAPV System:

The Chart 4.18 illustrates the normalized energy production and loss factors for a PV system with a nominal power of 300 Wp over a year. Energy supplied to the user accounts for the largest share at **75.4%**, while losses are distributed as **collection losses (Lc)** from the PV array at **12.6%**, **system and battery losses (Ls)** at **5.9%**, and **unused energy (Lu)** due to a full battery at **6.1%**. The monthly distribution remains consistent, indicating stable system performance and energy delivery throughout the year, while highlighting areas for potential efficiency improvements, such as reducing collection and system losses.

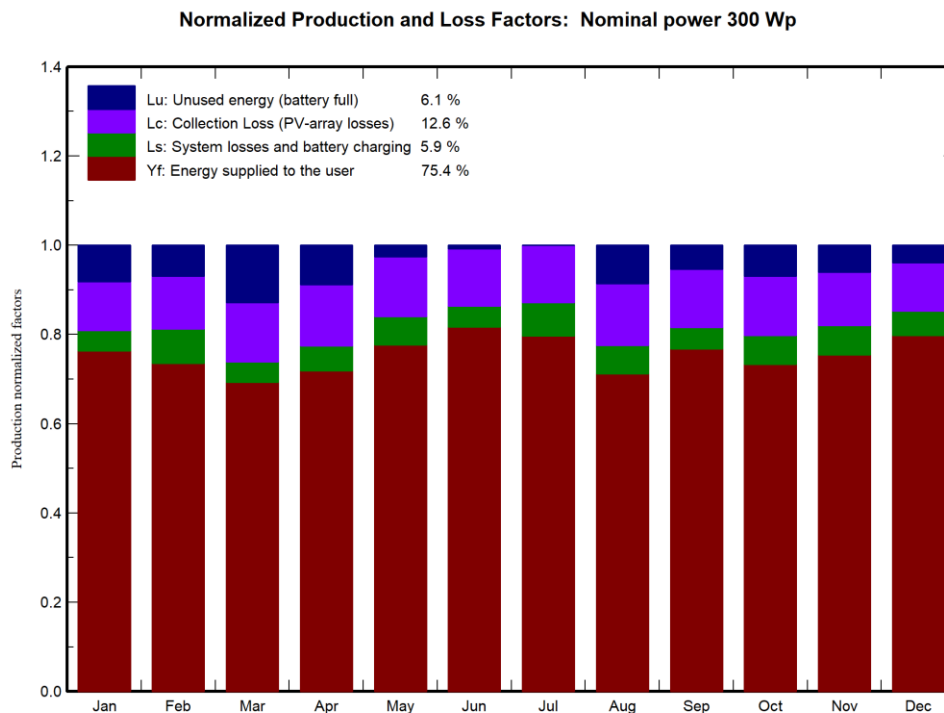


Fig. 4.18: Normalized Production and Loss Factor of the System.

4.2.3 Daily Input-Output Power Diagram of this SAPV Project

Figure 4.19 illustrates the daily Input-Output diagram of the SAPV system, showing the variation in energy production (kWh/day) relative to changes in global incidence on the collector plane over a year. The majority of data points indicate energy production exceeding 1.157 kWh per day. This suggests that the SAPV plant can consistently generate at least 1.157 kWh of energy on most days throughout the year.

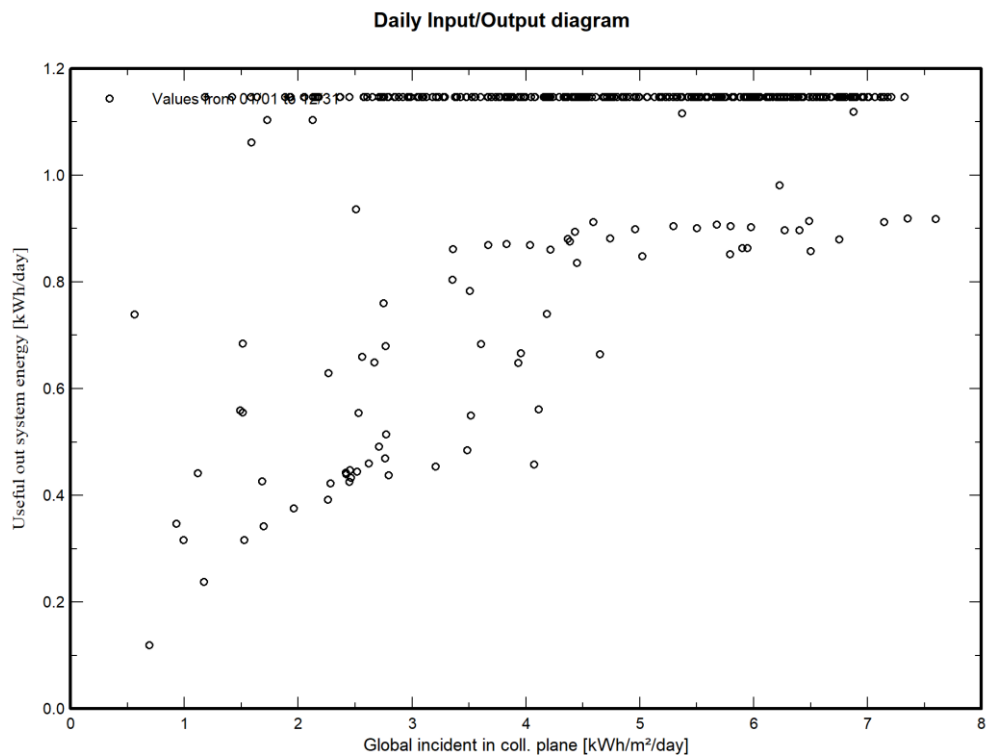


Fig. 4.19: Daily Input output power scenario of the APV System.

4.2.4 Daily Array Output Energy

Figure 4.20 illustrates the daily array output energy over a year, showing the effective energy output from the solar array in kWh/day.

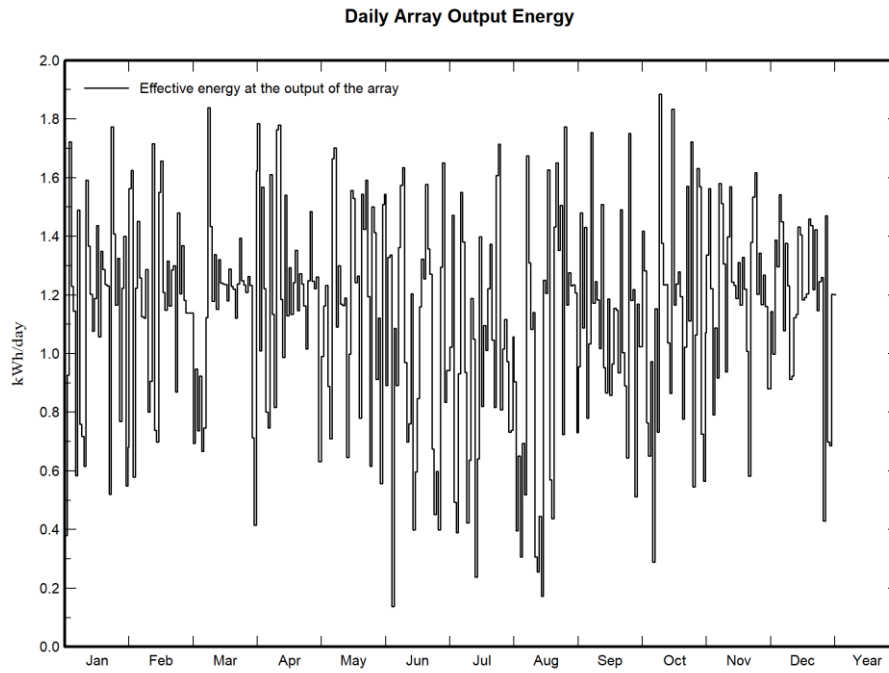


Fig. 4.20: Daily Array Output Energy

The output fluctuates between approximately **0.4 kWh/day** and **1.8 kWh/day**, reflecting seasonal and daily variations in solar irradiance. Peak outputs are observed during months with higher solar availability (such as summer), while lower outputs occur during periods with reduced sunlight (Such as winter or overcast days). The variability highlights the dependency of solar energy production on environmental conditions and the need for energy storage or supplementary systems to ensure consistent energy supply.

4.3 OUTPUT OF THE SOLAR PANEL SHADING ANALYSIS

Table 4.3 depicts the summary of the solar panel shading analysis with respect to load variation and shading percentage. In the first case study, the solar panel voltage was 48 volts, but after adding a load such as a fan, the voltage dropped to 23 volts. However, due to the shading effect, voltage also decreases in case study-3 and 4. In case study 5, the voltage is fluctuating due to Fan switching (low, medium, and high). Moreover, in case study 6 to 8; total 5 light is used as loads, where each light contains 5 watts in different shading conditions. However, due to shading decreases, the voltage increases, respectively. In case

study 9 to 11; irrigation motors were used as loads with different shading conditions. However, as the shading effect increases, the voltage is also decreasing respectively. Irrigation motor starting and water elevation conditions have different voltages. Finally, in case study 12 to 14; fan, light, and irrigation motor were used as loads with different shading conditions. However, decrease with the shading effect, the voltage is increasing, respectively.

Table 4.3: Summary of the solar panel shading analysis respect to load variation and shading percentage.

Case Study SL No	Shading percentage (%)	LOAD VARIATIONS	VOLTAGE (V)
CASE STUDY-01	0 %	NO LOAD	48 V
CASE STUDY-02	0 %	FAN	23 V
CASE STUDY-03	33.3 %	FAN	14 V
CASE STUDY-04	66.6 %	FAN	11 V
CASE STUDY-05	100 %	Fan *LOW, MEDIUM, HIGH	0.93 V, 0.44 V, 0 V
CASE STUDY-06	66.6 %	LIGHT	11.96 V
CASE STUDY-07	33.3 %	LIGHT	12.75 V
CASE STUDY-08	0 %	LIGHT	13.2 V
CASE STUDY-9	0%	Irrigation Motor *STARTING AND WATER ELEVATION CONDITION	42.06 V, 5.58 V
CASE STUDY-10	33.3 %	Irrigation Motor *STARTING AND WATER ELEVATION CONDITION	29 V, 4.5 V
CASE STUDY-11	66.6 %	IRRIGATION MOTOR	12 V
CASE STUDY-12	66.6 %	FAN + LIGHT + IRRIGATION MOTOR	0.73 V
CASE STUDY-13	33.3 %	FAN+ LIGHT + IRRIGATION MOTOR	0.82 V
CASE STUDY-14	0 %	FAN + LIGHT + IRRIGATION MOTOR	9.1 V

4.4 LER ANALYSIS OF THE PROPOSED APV SYSTEM

Here, Land Equivalent Ratio (LER) is calculated using total eight crops such as Tomato, Brinjal, Green chili, Lettuce, Cucumber, Alo vera, Snake-gourd, and Rose flower under APV and without PV panel shade. Table 4.4 depicts the Status of plants according to LER theory. Table data clearly said that brinjal, lettuce,

cucumber, rose flower, and alo vera are yield advantageous. On the other hand, green chili and snake-gourd are yield disadvantageous. Lastly, tomatoes under APV and without shading have the same output, which means No yield is advantageous.

Table 4.4: Status of plants according to LER theory

Crops	LER	Status
Tomato	1	No Yield Advantages
Brinjal	1.93	Yield Advantages
Green chili	0.96	Yield Disadvantages
Lettuce	1.85	Yield Advantages
Cucumber	2.1	Yield Advantages
Snake-Gourd	0.93	Yield Disadvantages
Rose Flower	2.6	Yield Advantages
Alovera	1.86	Yield Advantages

4.5 OPTIMIZING AGRIVOLTAICS SYSTEMS: CROP YIELD AND SOLAR POWER POTENTIAL ON 1 BIGHA OF LAND IN BANGLADESH

Table 4.5: Crop Production Under Agrivoltaics Systems: A Case Study for 1 Bigha Land.

Crops Investigated on APV System	Crops production using 9 m ² of land (Kg)	Crops Production using 1 Bigha (1338 m ²) of land (Kg)	Crops Production using 802.8 m ² of land (Assume 40% PV coverage of the total 1338 m ² area)	Yield on Shaded Area (535.2 m ²) (Kg)	Actual Total Yield (kg)
Tomato	2.45	364.23	218.30	166.46	334.94
Brinjal	3.5	520	305.06	162.78	467.84
Green Chili	0.55	81.76	48.17	25.69	73.86
Lettuce	0.95	141.23	80.28	42.82	123.10
Alo vera	3.4	505.46	297.04	158.14	455.18
Cucumber	1.75	252.73	155.74	82.83	238.57
Snake gourd	4	595	353.23	187.65	540.88
Rose Flower	3 P	446 P	265 P	141 P	407 P

4.6 SUMMARY AND CONCLUSIONS

This chapter presents a detailed performance and outcome analysis of the stand-alone Agrivoltaics (APV) system. The study examines gardening plantations under both shaded and non-shaded conditions, focusing on eight crops: aloe vera, cucumber, tomato, brinjal, green chili, lettuce, rose flowers, and snake gourd. Comparative analysis is conducted based on parameters such as plant height, number of leaves, number of flowers and fruits, size, and fruit weight. Data collected over eleven weeks is used to evaluate the system's agricultural impact. The chapter also includes a performance analysis of the stand-alone APV system using PVsyst software, with key metrics such as performance ratio, solar fraction, and normalized production being assessed. The system is modeled with a nominal power of 300 Wp, comprising three 100-watt solar panels. The chapter provides a daily input-output diagram and investigates the electrical shading impact, considering a shading coverage of 33.3% per panel. Additionally, the system supports three types of electrical loads: irrigation motors, DC lights, and table fans. The analysis of these loads is integrated into the study to evaluate the system's overall efficiency. Finally, the Land Equivalent Ratio (LER) of the APV system is calculated, demonstrating its profitability and viability for combined agricultural and photovoltaic applications.

5 System Losses

This chapter presents a comprehensive analysis of system losses of a stand-alone Agrivoltaic (APV) system. Section 5.1 focuses on evaluating the system losses associated with the APV system, identifying key contributors to performance degradation. Finally, Section 5.2 provides a summary of the chapter's findings and concludes with key remarks.

5.1 SYSTEM LOSSES IN STAND-ALONE AGRO-PV SYSTEM

The stand-alone PV project fell short of achieving 100% solar energy utilization due to various losses. Figure 5.1 is a schematic of the overall system loss during site installation. Solar radiation potential and ambient temperature had a significant impact on the PV array's output energy [106]. The provided loss diagram illustrates the annual energy flow and efficiency losses in a 300-watt agro-photovoltaic (APV) system. The system receives an initial global horizontal irradiation of 1589 kWh/m², which is adjusted to 1644 kWh/m² after accounting for a 6.4% gain in global incident irradiation and a 2.8% reduction due to the Incidence Angle Modifier (IAM) factor. After PV conversion efficiency (14.72%), the array nominal energy is 493.62 kWh, with further losses attributed to irradiance levels (-0.8%), temperature effects (-6.8%), module quality (-0.8%), array mismatch (-1.0%), and wiring losses (-2.4%). This results in 444.78 kWh of array virtual energy at the maximum power point (MPP). Additional losses include unused energy due to battery limitations (-7.0%) and converter inefficiency (-4.4%), yielding 418.29 kWh of usable energy. Of this, 44.3% is used directly, and 55.7% is stored, with minor losses (-1.3%) during battery storage. The diagram highlights inefficiencies across the system, emphasizing opportunities for optimization.

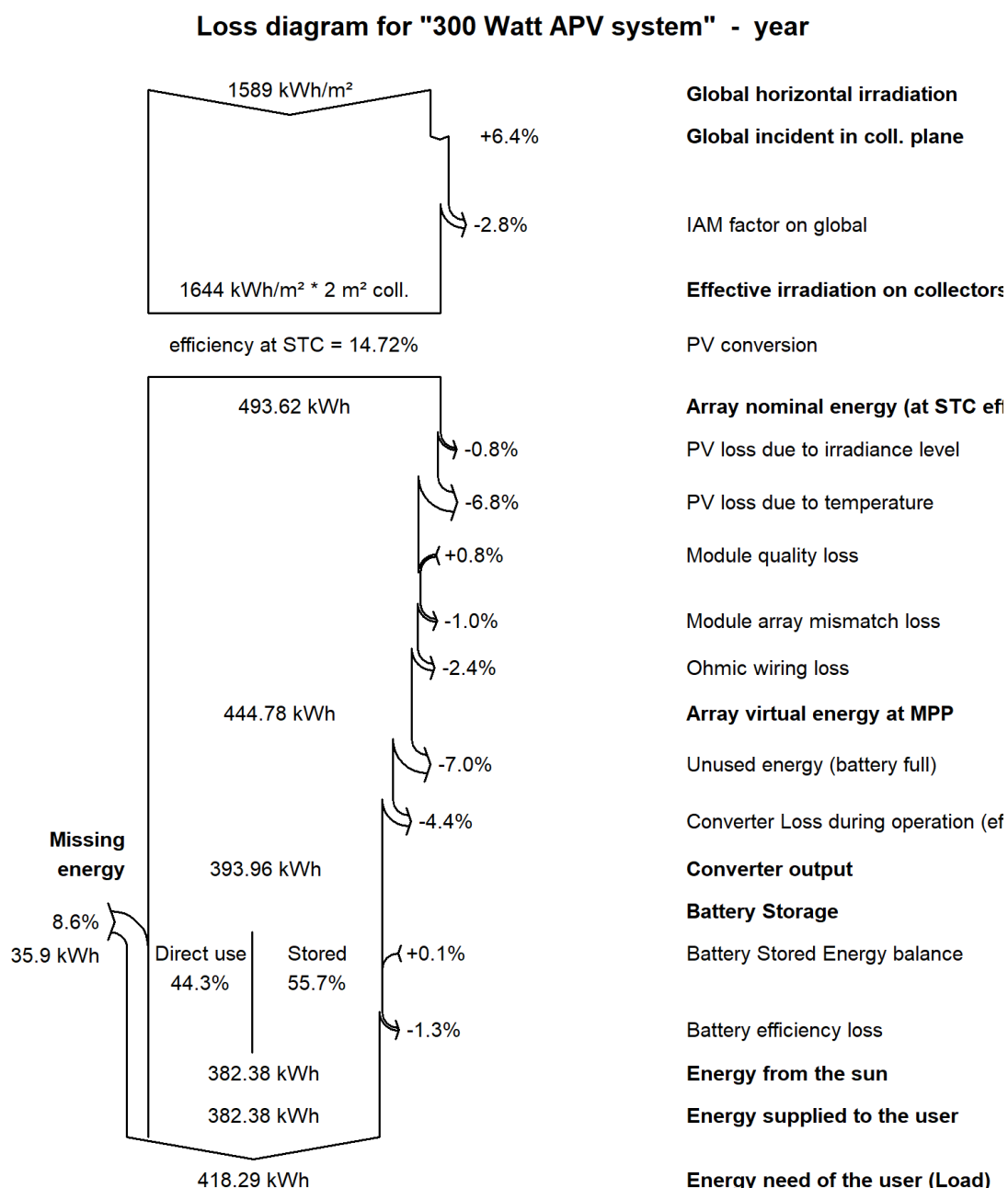


Fig. 5.1: Energy Flow and Loss Diagram for 300-Watt APV System (Sankey diagram)

Table 5.1: Summary of Annual Energy Flow and Loss Analysis for 300-Watt APV System.

Energy Flow/Stage	Value (kWh)	Loss/Effect (%)	Description
Global Horizontal Irradiation	1589	+6.4%	Global incident irradiation increases due to optimal angle.

Global Incident on Collector Plane	1644	-2.8%	Loss due to IAM (Incidence Angle Modifier) factor on global irradiation.
Effective Irradiation on Collectors	493.62	Efficiency at STC = 14.72%	Irradiation converted to array nominal energy at standard conditions.
Array Nominal Energy (STC)	493.62	-0.8%	Loss due to irradiance level.
		-6.8%	Loss due to temperature.
		+0.8%	Gain due to module quality.
		-1.0%	Loss due to module array mismatch.
		-2.4%	Loss due to ohmic wiring.
Array Virtual Energy at MPP	444.78	-7.0%	Loss due to unused energy when the battery is full.
Converter Output	393.96	-4.4%	Converter loss during operation.
Battery Stored Energy Balance	393.96	+0.1%	Small gain due to balancing stored energy.
Energy From Battery (After Efficiency)	382.38	-1.3%	Loss due to battery efficiency.

5.2 SUMMARY AND CONCLUSIONS

This chapter evaluates the system losses of a stand-alone Agrivoltaics (APV) system. Using PVsyst software, the analysis simulates energy losses, starting with global horizontal irradiation of 1589 kWh/m² and calculating a final usable energy output of 418.29 kWh after losses. Battery storage efficiency is determined to be 78.5%, reflecting the actual energy delivered to the load.

6 Conclusions and Future Work

So far, this chapter provides a comprehensive summary of the research and simulation results presented throughout the thesis. It consolidates the key aspects of the study, including the introduction, methodology, results, and discussion from the previous chapters, while offering a concise conclusion of the overall research conducted. The chapter is structured to provide a clear overview of the study's key findings, limitations, and implications, along with recommendations for future research. Section 6.1 presents a summary of this research without detailed interpretation. The significant findings are tied together, and a few possible implication issues are in Sections 6.2. Recommendation for further study is explained in section 6.3.

6.1 SUMMARY

The developed model successfully addresses the challenges of sustainable land use by integrating food and energy production through agro-photovoltaic (APV) technology. This research demonstrates the feasibility of cultivating shade-tolerant crops under shaded and unshaded conditions within a standalone photovoltaic (SAPV) system, ensuring both agricultural productivity and energy generation. Using the Land Equivalent Ratio (LER) method, the study optimizes crop yield, predicts system losses, and performs an economic analysis of the SAPV system. Key plant growth parameters, including plant height, leaf count, flower count, fruit count, and fruit weight, were assessed to evaluate crop performance under solar shading. The study's findings reveal that crops such as brinjal, lettuce, aloe vera, cucumber, and rose flower exhibit significant yield advantages within the APV system, while green chili and snake gourd are yield-disadvantaged, and tomatoes show no notable yield differences. From an energy perspective, the SAPV system achieved an average yearly performance ratio of

75.4% and a solar fraction (FR) of 0.914, producing sufficient energy to meet load demands. Simulations and practical data indicate an average daily production is 1.157 kWh. Furthermore, the APV system enhances land use efficiency by reducing excessive land utilization and improving water use efficiency through the shading effect, which lowers evapotranspiration. The system's surplus electricity can be fed into the grid using a net metering system, creating opportunities for passive income.

Key Insights:

- **Dual-purpose land use:** APV technology effectively combines food and energy production, addressing the challenges of sustainable land use.
- **Optimization through LER:** The Land Equivalent Ratio (LER) method ensures maximum crop harvesting and efficient resource utilization.
- **Shade-tolerant crop viability:** The study identifies commercially viable shade-tolerant crops for the APV system through detailed analysis.
- **Electrical shading impact:** Investigations into electrical shading highlight the need to balance crop growth and energy generation to maximize system efficiency.
- **Environmental benefits:** By shading the ground, the APV system reduces evapotranspiration, increases water use efficiency, and promotes sustainable agricultural practices.

In summary, this study confirms the potential of APV technology as a sustainable solution for integrated food and energy production. Its ability to reduce land use conflicts, lower energy costs make it a promising approach for addressing Bangladesh's future energy and agricultural challenges.

6.2 IMPLICATION

The integration of stand-alone agro-PV systems on arable land highlights a trade-off between solar power generation and sustainable development goals. While agro-PV reduces energy imports, creates jobs, and drives innovation, its

use of fertile land primarily for energy production may conflict with policies focused on agricultural productivity and food security. To address this, performance assessments should consider land-use efficiency, ecosystem impacts, and socioeconomic benefits, ensuring agro-PV systems align with sustainability objectives.

6.3 RECOMMENDATION FOR FURTHER STUDY

- **Grid-Connected Agro-PV Systems:** Future studies should investigate the integration of larger AC loads and diverse crop harvesting techniques to evaluate the commercial viability of grid-connected agro-photovoltaic systems using net metering system.

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Appendices

APPENDIX A: ELECTRICAL SHADING ANALYSIS CODING

The majority of the time, leaf's cover the solar panels in an actual Agro-photovoltaic system. The solar panel is unable to produce the output correctly as a result. We looked into electrical shading analysis in the stand-alone Agro-PV system to support this issue. We measured the generating voltage and current variation both with and without shade in this regard. However, microcontroller-based project is setup to acquire the data. Respected coding is attached below;

```
const int VIN = A0; // define the Arduino pin A0 as voltage input (V in)
```

```
const float VCC = 5.00; // supply voltage
```

```
const int MODEL = 2;
```

```
#include <Robojax_AllegroACS_Current_Sensor.h>
```

```
Robojax_AllegroACS_Current_Sensor robojax(MODEL,VIN);
```

```
void setup()
```

```
{
```

```
Serial.begin(9600);
```

```
pinMode(1,INPUT); //voltage
```

```
}
```

```
void loop ()
```

```
{
```

```
// voltage
```

```
float vo=analogRead(1);
```

```
vo = map(vo,0,1024,0,50);
```

```
float lt = analogRead(1) / 1023.0 * 5.00;
```

```
double volt = (vo + lt);
```

```
Serial.println(volt);
```

```

        Serial.print("\t");
        // current
        Serial.print(robojax.getCurrentAverage(500),3);//
        Serial.println("A");
        Serial.print("\t");
        // robojax.debug();

        float power = (robojax.getCurrentAverage(500),3)*(volt);
        Serial.println(po.wer);
        Delay (1000);
        unsigned long startTime = millis(); // get the start time in milliseconds
        while (millis() - startTime <= 10000)
        {
            // your code here

            Serial.println("Program is running...");
            Delay (1000); // add a delay to prevent flooding the serial monitor
        }
        exit(0); // exit the program after 1 minute
    }

```

APPENDIX B: ELECTRICAL SHADING ANALYSIS CONSIDERED LIGHT AS LOAD WITH THREE PANEL SHADING

In this study, Figure B01 shows 100 percent shading and used electric light as a load. Total 5 light is used where each light contains 5 watts.



Fig. B01: Considered Light as Load With Three Panel Shading

Table B01 shows data from an Arduino serial monitor. The time interval of every data point is 10 seconds. In this study, considered three panels shading and used light as a load. Although three panels are fully shaded, some portions of the panel are slightly uncovered, and the previous voltage shows an increased value, which is approximately 7.38 volts. However, due to full shading, load current and power consumption are small.

Table B01: Voltage, Current and Power variations in-terms of three panel Shade and used Load as Light.

Voltage (V)	Current (I)	Power (P)
7.37	0.07	0.52
7.32	0.069	0.51
7.37	0.069	0.51
7.32	0.068	0.5
7.32	0.068	0.5
7.37	0.068	0.5
7.32	0.067	0.49
7.37	0.069	0.51
7.32	0.063	0.46
7.32	0.066	0.48
7.42	0.073	0.54
7.37	0.062	0.46
7.42	0.07	0.52
7.42	0.071	0.52
7.37	0.071	0.53
7.37	0.072	0.53
7.32	0.07	0.51
7.32	0.068	0.5
7.37	0.068	0.5
7.37	0.065	0.48
7.37	0.069	0.51
7.37	0.068	0.5
7.32	0.07	0.52
7.32	0.07	0.51
7.37	0.067	0.49
7.37	0.07	0.52
7.37	0.069	0.51
7.37	0.069	0.51

APPENDIX C: AFFECTED PLANT IN SAPV PROJECT

In Figure C01 shows Squash plant which affected insects. Calcium is one of the many minerals abundant in squash. In order to maintain strong bones and teeth, calcium is essential. Squash is a good source of vitamins A and C, which helps support strong bones. In fact, a 2017 analysis of studies found a connection between vitamin A deficiency and a higher risk of bone fractures. However, Squash is uprooted as it was affected by insects.



Fig. C01: Squash plant affected by insects.

APPENDIX D: CROPS (TOMATO) POTENTIAL ON 1 BIGHA OF LAND IN BANGLADESH

- Shading Effect:
 - Assume 40% PV coverage of the total area (1338 m² area)
- Yield reduction under shading: 20% reduction for Tomato.
- Effective Area for Farming: 1,338 m² total land area.
- 60% of land receives sufficient sunlight for optimal farming, equivalent to 802.8 m².

- Tomato Yield in Open Field Conditions:
 - Tomato production per square meter: 0.2722kg/m^2
 - Open-field yield on 802.8 m^2 : $0.2722\text{ kg/m}^2 \times 802.8\text{ m}^2 = 218.48\text{ kg}$
- Adjusted Yield Under Shaded Conditions:
 - Shaded area: 535.2 m^2 (40% of $1,338\text{ m}^2$)
 - Yield reduction under shade: 20%
 - Adjusted brinjal production in shaded area:
 $0.2722\text{ kg/m}^2 \times 80\% \times 535.2\text{ m}^2 = 116.46\text{kg}$
- Total Production Under APV:
 - Adding the yields from Open Field Conditions and shaded areas:
 - $218.48\text{ kg} + 116.46\text{ kg} = 334.94\text{ kg}$

APPENDIX E: SOLAR POWER POTENTIAL ON 1 BIGHA OF LAND IN BANGLADESH

- Energy production for 9 m^2 : 418.29 kWh/year .
- Total land area: $1,338\text{ m}^2$.
- PV coverage ratio (as per APV system): 40%.
- Determine Energy Production per m^2 : $\frac{418.29\text{ KWh}}{9\text{m}^2} = 46.477\text{KWh/m}^2$.
- Calculate PV-Covered Area: In the APV system, 40% of the total area is used for PV installation: $1,338\text{ m}^2 \times 40\% = 535.2\text{ m}^2$
- Calculate Total Energy Production:
 - $535.2\text{ m}^2 \times 46.477\text{kWh/ m}^2 = 24,875.88\text{kWh/year}$

Using **$1,338\text{ m}^2$ of land**, the **APV system** can generate approximately **$24,876\text{ kWh}$ per year**.