Development of Floating PV Test Bench and its Comparison with On Ground PV System

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Session 2019-21

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February 2022

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A Thesis Submitted to the US-Pakistan Center for Advanced Studies in Energy in partial fulfilment of the requirements for the degree of
MASTERS of SCIENCE in
Energy Systems Engineering

US-Pakistan Centre for Advanced Studies in Energy (USPCAS-E)
National University of Sciences and Technology (NUST)
H-12, Islamabad 44000, Pakistan
February 2022

THESIS ACCEPTANCE CERTIFICATE

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Dedication

The thesis is wholeheartedly dedicated to my beloved parents and my supervisor Dr. Adeel Waqas. A special thanks to Dr. Nadia Shahzad, Dr. Sehar Shakir and Sir. Abdul Kashif Janjua for pushing me forward in times when I struggled. I am thankful for their love and measureless support. All of you have been a driving force throughout this process.

Abstract

Solar energy is a promising technology for producing cost-effective, long-term green energy. Floating Photo Voltaic (FPV) technology is a relatively new concept for producing clean green energy. FPV combines a floating structure with an existing PV system, allowing for increased PV module efficiency. FPV offers an alternative to the high cost of land for On-Ground PV (OPV) systems while mitigating the environmental effects caused by OPV systems. Local environmental factors such as air temperature, wind speed, humidity, and solar flux have a significant impact on PV systems. Furthermore, FPV systems aid in the reduction of water evaporation, resulting in water savings. The experimental investigation of a small-scale FPVS is presented in this study. It is intended for research and demonstration purposes only, as a first attempt to analyze this concept under Pakistani operating conditions. The goal is to analyze and compare the thermal and electrical performances of mono and polycrystalline PV modules used in FPV with those of an OPV system with a similar nominal capacity, as well as to investigate the effect of FPV on water evaporation. To accomplish this, a test bench comprised of an FPV and an OPV system, as well as a measurement station, has been proposed and developed. This paper elaborates on the experimental setup of the complete test bench. The results show that when the water body is partially covered with an FPV system, water evaporation is reduced by 17%, and it is reduced by around 28% when fully covered. It was also found that water bodies provide an adequate cooling effect, lowering the front temperature of FPV modules by 2-4% and the back temperature by 5-11% when compared to OPV modules. Thermal imaging revealed that at 0 degrees of tilt, the front temperatures of the modules are uniform, but as the tilt increases, a temperature gradient is observed between the bottom and middle parts of the modules. In addition, an experimental test was carried out in this work to compare the energy production of FPVS at different tilt angles. The test results show that when the FPV system is installed at the annual optimal tilt angle, it produces the most energy. As a result, adjusting the PV modules to their optimal tilt angle is also suggested for FPV.

Keywords: Floating photovoltaic system (FPV); Floating PV modules; Water Cooling; Humidity; Evaporation, Pakistan

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List of Papers

1. **Hamza Nisar**, Abdul Kashif Janjua, Hamza Hafeez, Sehar Shakir, Nadia Shahzad, Adeel Waqas "Thermal and Electrical Performance of Solar Floating PV System Compared to On-ground PV System-An Experimental Investigation"
   Journal: Renewable Energy, 2021 (Under revision)

2. Hamza Hafeez, Abdul Kashif Janjua, **Hamza Nisar**, Sehar Shakir, Nadia Shahzad, Adeel Waqas "Technoeconomic Assessment of Floating Solar PV deployed Over A Local Lake for Grid Connected Loads In Developing Countries"
   Journal: Solar Energy, 2021.
   DOI: https://doi.org/10.10.16/j.solener.2021.11.071

List of Abbreviations

Res	Renewable Energy Sources
PV	Photovoltaic
FPV	Floating Photovoltaic
OPV	On Ground Photovoltaic
STC	Standard Test Condition
RPS	Renewable Portfolio Standard
kW	Kilo Watt
MW	Mega Watt

Chapter 1: Introduction

1.1 Background

Increased global warming, growing demand for energy, and depletion of fossil fuels have enabled demand and penetration of Renewable Energy Sources (RES). RES is seen as environmentally friendly, are suitable for fulfilling the growing energy demand [1]. Solar energy sources are of interest, having diverse ways to utilize the technology and has potential to replace the conventional power sources. Photovoltaic (PV) is the most prevailing technology for utilizing solar energy, which produces electricity by absorbing the sunlight directly [2]. Around 40% of the overall world electricity generation demand is forecasted to be accomplished by solar PV systems by 2050 [3]. Land acquisition for energy projects could be difficult in some areas due to the non-availability of land and considering the impact that land cannot be used for other general purposes e.g., agricultural use. It is vital to explore the potential application of technologies that optimize natural resources, existing infrastructure and improves the energy generation of renewable sources while taking account of climate change and water scarcity. The floating Photovoltaic (FPV) System is the most promising application of PV technology, which delivers the above conditions. It is an alternative to a ground-mounted PV system, deployed on water bodies such as ponds, lakes, rivers, canals, dams, etc. [4]. FPV system combines both solar technologies and floating applications. FPV can be deployed in highly populated countries like Japan, the USA, etc. And can find its applications when there is a limited area or high cost of land for a large-scale ground-based PV system, in dry areas where there is a need to reduce water evaporation or there is a requirement of higher efficiency, power generation [5].

1.2 FPV System

FPV system consists of floating units, PV modules and mounting structure, mooring system, and inverters. Floating units are bouncy units used to keep the structure floating on the water body, on top of which PV panels are mounted directly or on a mounting structure. To keep the floating structure in place a mooring system is used [6]. Although there are many advantages of an FPV system, there are also some critical challenges that should be assessed site by site. As these installations are done on a water body, they are vulnerable to waves and storms which can destroy or affect the life of the FPV plant [7]. In the FPV system, more environmental dynamic loads are resulting in greater fatigue loads as compared to on Ground Photovoltaic (OPV) System. Moreover, there are some environmental impacts too which should be considered while deploying the system such as the potential impact on biodiversity due to lack of sunlight [8]. FPV systems face different challenges as compared to OPV systems, similar challenges have come upon offshore projects which integrate floating systems. Proven floating technologies can be drawn from the offshore fields for the FPV application installation [9].

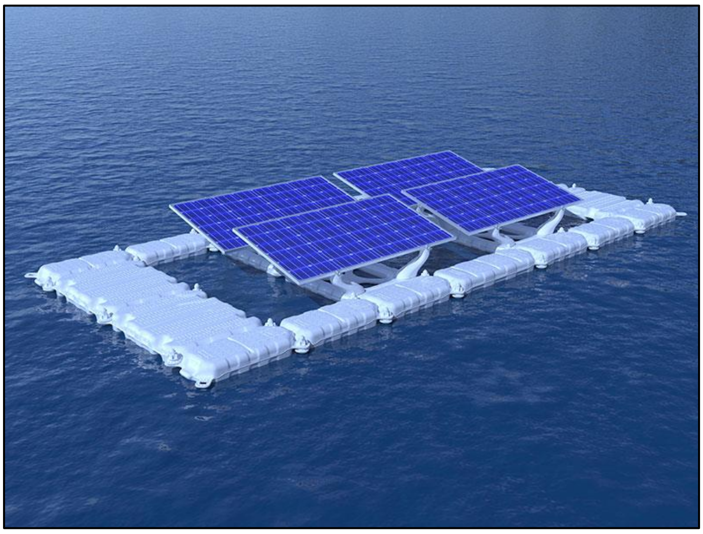

Figure 1.1 Floating PV System

1.3 Problem Identification

It is important to assess the feasibility, profitability, and yield of an FPV system in a specific environment. As compared to an OPV system, 15% of gains are reported in an FPV system [10]. For a better assessment of FPV energy estimates, it is important to understand weather conditions and the thermal behavior of a water body. PV modules are rated on Standard Test Conditions (STC), which is 1000 W/m^2 and 25 ^{0}C PV. Above 25 ^{0}C module surface temperature, electricity generation is reduced as temperature increases. It is reported that per degree rise in surface temperature of PV module efficiency drop by 0.44% [11]. FPV systems have the benefit of lower module temperature as compared to OPV systems due to natural cooling provided by lower air temperature during the day, provided by the water body. Around 13% of energy gain was seen when an FPV system and OPV system were compared situated 60km apart [12]. A study conducted in Singapore showed that there had been a 5-10% gain in efficiency of FPV testbed when compared to the rooftop-based PV system. Many environmental factors such as wind speed, humidity, solar radiation, etc. [13]. affect the performance of the PV system. Also, in an FPV system, energy gain depends on the location of the system on a water body, hence performance ratio may defer from location to location [14].

1.4 Justification of Research

FPV is one of the hottest topics in the field of renewable energy technologies. Most of the research carried out is on a large scale, requiring a lot of funding. It would be of interest to develop a small-scale FPV testbench to study the impact of the environment on an FPV system and to assess its potential in a specific location. Such a study would not only enable students to research this topic but would also encourage the development of FPV plants in a developing country like Pakistan. A small-scale test bench has already been developed in Morocco, but still, there is a need to fully automate the testbench to make data acquisition accuracy for better results and analysis [15]. Also, no testbench has been developed yet to study the performance of both mono and polycrystalline PV modules. The proposed research is focused on developing a small-scale FPV test bench with a fully automated measuring station including instrumentation to measure thermal, electrical, and weather parameters required for the analysis of the PV system. It is designed to study the performance of mono and polycrystalline modules at different tilt angles. No research has been done till now that presents the assessment of the FPV system in Pakistan on a testbench level. Pakistan is a developing country with great energy potential from solar plants and has been investing in solar projects to meet the increasing energy demand. Implementing FPV would be an interesting opportunity for Pakistan as it would save water in a water body by reducing evaporation and providing better electricity generation benefits. Most of the water bodies are located near agricultural land with many populations. FPV system would not only provide electricity for domestic use for this population but would also save water for agricultural use. Merging an FPV system with a hydroelectric power station would not only increase the hydro station power generation by reducing the water loss but would also reduce the cost of grid connection infrastructure. This work would explore the potential of the FPV system under the climatic conditions of Pakistan and will compare the performance with the OPV system.

1.5 Scope of Research

A critical analysis and comparison are required between the Floating PV system (FPV) and On-Ground System (OPV), to compare and test the efficiency and benefits of the system. To investigate, a test bench is proposed consisting of OPV and FPV system along with a data measuring station. The measuring station is developed consisting of several measuring sensors and instruments to measure the metrological parameters electrical parameters, and PV modules temperature that are used in the test bench. Target of the proposed test bench is to determine the rate of evaporation under different conditions in FPV system, to compare the thermal difference between the OPV and FPV system modules and to compare the electrical efficiency of Mono and Poly PV modules used in both systems. The experiments are conducted at different tilt angles to observe the effect of cooling in FPV system and its effect on performance efficiency.

1.6 Objectives of Research

The major objective of the research is to compare the electrical and thermal performance of FPV and OPV system.

- To develop a small scale FPV system using pond simulator.
- To develop a data logger to gather data of electrical, thermal, and metrological parameters.
- To measure the rate of evaporation from FPV pond simulator at different conditions.
- To determine and compare the thermal performance of Mono and Poly crystalline PV modules in FPV and OPV system.
- To determine and compare the electrical performance of Mono and Poly crystalline PV modules in FPV and OPV system.
- To determine the cooling effect at different tilt angles.

1.7 Limitation of Research

The research carried out is based on small scale test bench, results of the experiment may vary in case of deployment on a water reservoir. Further the research carried out is inside of an educational institution which does not reflect the scenario when the actual FPV system is deployed as factors like water reservoir license and social acceptability would also be needed to be addressed. Moreover, the designing of the floating system need to be classified according to the water depth and location of the

FPV system. The data logger currently being used can be improved by collection of data via online Wi-Fi access point rather than physical interaction as it consumes unnecessary time and decreases the accuracy of data by turning of the datalogger while measuring readings. The test bench requires a water cleaning system as due to stagnant water inside the water reservoir fungus starts to grow and form a layer on top of the water surface. The test bench also needs a small cleaning system for PV modules to remove soiling as PV panels has soil accumulation after one week. The weather data collected for Islamabad weather conditions and the FPV results may vary when it is deployed in hotter more humid locations other than Islamabad.

Thesis Flow

Introduction: Background of FPV system, Problem Identification, Justification of Research, Scope of Research, Objective of Research, Limitation of Research.

⇩

Literature Review: Significance of FPV System, FPV System, FPV’s Advantage, Potential Challenges, FPV Power Generation, FPV System and Evaporation, Factors Effecting Performance FPV System.

⇩

Research Methodology: Testbench and its Targets, Proposed FPV System Design, Description and experimental setup.

⇩

Results and Discussion: 0 Degree Test, 15 Degree Test, 30 Degree test, Thermal Comparison between Different Tilt angles, Power and Optimal Tilt angle.

⇩

Conclusion and Future Recommendation: Conclusion and Future Recommendation

Summary

The most promising application of PV technology is the floating Photovoltaic (FPV) System. PV modules and floating units are combined in FPV. And it can be used when there is a limited amount of land available, or the cost of land is prohibitively expensive for a large-scale ground-based PV system. The FPV system has a reported energy gain of 5-13 percent when compared to the on-ground PV system. The energy gain of an FPV system is affected by a variety of metrological conditions. It is critical to investigate the impact of prevailing climatic conditions in a specific location on the performance of an FPV system.

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Chapter 2: Literature Review

2.1 Background

The crisis of climate change and global warming due to the burning of fossil fuels has strongly affected mankind. For this reason, renewable energy sources are subject to increased demand and interest at a rapid rate all around the globe and due to the introduction of the Renewable Portfolio Standard (RPS). Over the last decade, renewable energy sources have had prodigious importance in the electricity sector. Solar energy is one of the most promising technology due to its sustainability and universality [1-2]. Photovoltaic systems (PV) are the most common application of solar energy. In the field of renewable energy, photovoltaic modules are the reliable, and eco-friendly [3-4]. The main constraint of using PV power technology lies in the extensive land use: a large surface area of land is required due to low PV panel efficiency (around 15%). Hence, 10,000 m^2 area of land is required for the solar power station of 1MWp, having a major environmental impact as land cannot be used for other general purposes e.g., agricultural use, housing. Due to this reason, there is a reduction in the market in Europe and North America [5]. For the quick expansion of this technology, the Floating Photovoltaic System (FPV) seems to be the promising option. Large water resources are available, and the cost of water-based PV solution is near to that of On-Ground PV (OPV) solution [6]. Moreover, FPV's take the advantage of natural cooling from water basins as compared to on-ground or roof-based PV systems [7].

2.2 FPV System

FPV is a new and emerging form of solar energy production, which allows PV panels to float on a water body's using floating structures. The FPV system consists of a floating platform, mooring system, PV modules, and distribution system [8] as shown in Figure 2.1.

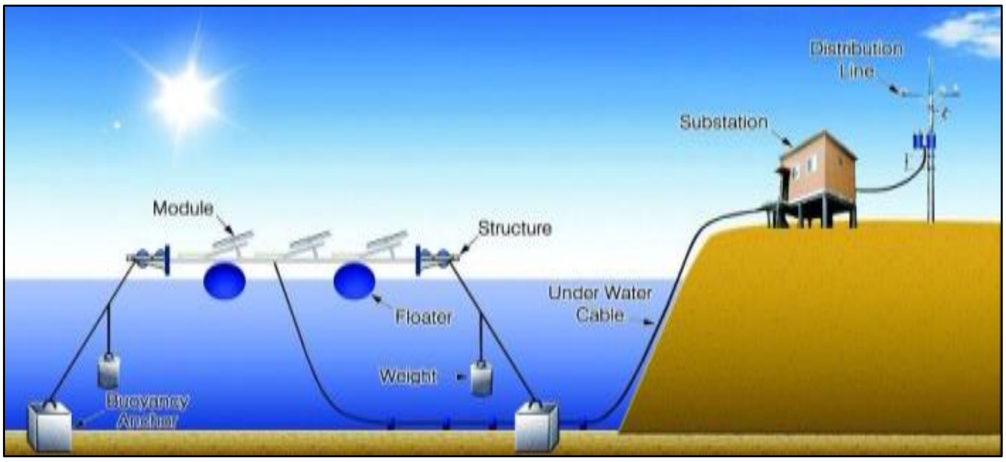

Figure 2.1: Layout of an FPV system [1]

A floating platform is made up of floats having enough bouncy to carry heavy loads and float itself. Floating platform is designed in such a way to carry number of modulus according to design requirements [59]. A mooring system is a permanent structure which helps to keep the floating system in place and prevents the system from turning from the location [60]. The world's first FPV system for research purposes was built in Archi, Japan in 2017 having a capacity of 20 kW [9]. Different floating systems have been installed in the USA, France, Korea, Italy, and Spain, etc. Various FPV developments were studied by Sahu [10] that have been comprehended over the years. Around 23 MW of FPV solar system has been installed in Japan while other countries like India, Canada, and Singapore also contribute to FPV installation alongside the hydropower stations [10-11].

2.3 Types of PV Installation

PV installations are classified into 5 types: ground mounted, rooftop, canal top, offshore and floating. Ground mounted PV systems are held in place using frames that are mounted to the ground base and are generally large-scale projects [10] as shown in Figure 2.2(A). Roof top PV systems are installed at the top of residential or commercial buildings. These systems are smaller as compared the ground mounted systems with capacities in range of 5kW-100kW [56]. Rooftop PV system is shown in Figure 2.2(B). Canal top solar systems are setup at the top of a canal, avoiding the use of large area of land deforestation as shown in Figure 2.2(C). However, efficiency of canal top PV plants has less efficiency as compared to ground-based PV plants [57]. Offshore solar PV installations are being exploited due to expensive land cost and non-availability of land. Offshore installations are a great way to exploit solar energy as oceans cover 70%

of the earth surface and receive a great amount of solar energy [58] as shown in Figure 2.2(D). Floating PV systems are installed on lakes and other water bodies with a floating body. These systems have higher efficiency as compared to the on-ground systems.

A B

C D

Figure 2.2: Types of PV Installations [9]

2.4 FPV’s Advantage

Floating PV structures have numerous advantages as compared to the on-ground systems; precisely:

- FPV system has no consequence on the albedo effect hence does not add to global warming. Whereas on the other hand, the on-ground system increases the earth's energy budget by reducing the local albedo [12].
- Potential of hydro and FPV hybrid power station, reducing the cost of transmission lines [13]

- Improving the water quality by reducing the algae growth as the FPV system provides shade to the water [14].
- FPV energy generation increase due to the increased reflectivity of solar radiation from the water surface hence increasing the amount of incident solar radiation on the PV module [15]
- Reduction in evaporation of water due to the shade provided by FPV’s. Literature reports that evaporation can be reduced by 25-70% depending on climatic conditions [16,17]
- Due to the natural cooling effect provided by water, FPV’s takes advantage and have better efficiency has compared to on-ground systems [18,19].

2.5 Potential Challenges

Based on the studies FPV’s have many beneficial environmental and economic benefits, also better energy efficiency. Along with these, there are also some potential challenges for the FPV system. Pimentel da saliva [20] studied that, due to the reduced solar radiation penetration in water bodies growth of aquatic animals is affected. Although FPV’s suffer less from the dust soiling effect, bird's soiling can greatly affect the FPV’s and can accelerate towards lower efficiency and module degradation. Therefore, looking into the process of cleaning birds soiling and scheduled maintenance would be worth considering [13]. FPV’s are subject to strong wind gusts, requiring many mooring points to maintain the position [21]. However, a lot of research is ongoing on FPV structure and mooring, Kim [22] worked on the construction of an FPV structural system using FRP members. Natarajan [23] developed a prototype of a dual axis tracking system for FPV’s.

2.6 FPV Power Generation

Installation of FPV systems has increased significantly over the years, as it has many multiple advantages. Numerous studies have been conducted on performance analysis, environmental impacts, floating structures, and economic feasibility. Studies indicate that a drop in efficiency of about 0.45% and 0.25% occurs in monocrystalline and polycrystalline PV panels due to an increase of only one-degree temperature [24]. Various methods have been proposed such as cooling effect by water or air, use of phase change materials, etc. [25-26]. The efficiency of PV modules is also decreased due to dust deposition [27]. The efficiency of the FPV system is more as compared to the OPV system due to the less dust deposition being away from the urban areas and due to the cooling effect [28].

Campana [29] studied the economic feasibility of tracking and still floating FPV’s and their integration within an off-grid hybrid system. Yadav [18] conducted a study on the performance analysis of the FPV system and its comparison with the conventional system. The study concluded that the FPV system has high power generation than the conventional system. Lee [30] researched the design and installation of the FPV system using the FRP members and did a comparison with the on-ground system in Korea. Technical and economic analysis of the FPV system was carried out by Santafé [31] for the irrigation reservoirs. The study states that 425.000 kWh/year of electricity is generated while saving 5000m^3 of water annually. Another similar study also states the economic feasibility of the FPV system [32]. Silvério [33] researched the hybrid system of floating and hydropower plants, results state that the hybrid system can add up to 76% of energy gain with a capacity factor of 17.3%. Kim [34] carried out a study to pre-analyze the potentiality of a reservoir for a floating PV system. Lee [35] studied numerical simulation to analyze the FPV system. Mathematical models showed that the system could withstand environmental stress such as wind loads. Huzaifa Rauf [36] analyzed the potential of techniques to integrate the floating PV system for the Ghazi Barotha dam while utilizing its transmission and distribution system.

2.7 FPV System and Evaporation

Choi [1] studied that the FPV system has better energy efficiency due to the cooling effect provided by the water body and the reflection of light from the water surface. Another study concluded that evaporative cooling increases FPV energy efficiency, but it also depends on geographic location. Also, the rate of evaporation depends on the fraction of covered area and geographic location [17]. Mittal [37] studied that around 91 to 708 million liters of water were evaporated from the lake area taken into the consideration without FPV and water saved from reduction evaporation due to the FPV system deployed varied from 64 to 496 million litters. Evaporation from a water body is not simple as it depends on many factors such as solar radiation, water thermal energy, relative humidity, wind speed, and water thermal equilibrium. Radiant energy exchange between the water surface and atmosphere significantly depends on atmospheric temperature and humidity [38]. There is an inverse relation of evaporation with relative humidity and is directly related to the wind speed. While relative humidity is also affected by the wind speed, it decreases as the wind speed increase [39]. Solar radiation with good transfer to the water body does not noticeably affect evaporation. While vapor pressure and wind speed greatly affect evaporation [40]. When the water body is covered with PV modules, wind speed is strongly reduced below the raft. Due to the conversion efficiency and reflection through PV modules, the water surface observes reduced thermal energy gain. Also, the cavity produced between PV modules and water surface vapor pressure approaches saturation pressure [41]. Covering the water body with floating units increases the water temperature, and the rate of evaporation is strongly reduced [42]. Another study also states that covering the water body changes the thermal equilibrium of the water body. Parts of the water body covered by PV modules hinder the energy entering the water body by 90%. Waterbody temperature slightly decreases even evaporation is strongly reduced due to the negative thermal balance of the water body. Reduction in solar radiation received by the water body affects the thermal equilibrium, the conduction mechanism helps to maintain a stable equilibrium [43].

2.8 Factors Effecting Performance FPV System

To understand the behavior of FPV technology temperature is a significant factor. Weather conditions are not same throughout the world due to the change in terrain, topology, and climate. In Pakistan, temperature can reach up to 50°C during day peak hours. Maximum solar energy can be gained during this period [36]. Although solar radiations are responsible for energy generation in PV system, but increase in temperature of PV system above an upper limit will decrease the efficiency of PV system. Due to the cooling effect from water, FPV's operating temperature is 3.5°C lower as compare to the OPV system [44]. Choi [1] studied that as compared to the OPV system, FPV system produce 11% more energy which is due the cooling effect provided by water. It is reported that per degree rise in surface temperature of PV module efficiency drop by 0.44% [11]. PV operating conditions can reach up to 80°C due to concentration of solar radiation [22]. Thus, energy efficiency of PV modules can be increased by installing them on a water body due to the cooling effect. Moreover, increased soiling and high humidity decrease the incident solar radiation and hence decrease PV power generation [45,46]. Research states that relative humidity affects incoming solar radiation by reducing the solar radiation due to reflection and radiation from vapors present in the atmosphere [47]. It is observed that

PV energy generation is adversely affected by increasing relative humidity [48,49]. Due to high relative humidity, adhesion of dust particles with PV modules increases, hence decease the PV energy efficiency. While relative humidity is also affected by the wind speed, it decreases as the wind speed increase. High wind speeds also have a downside of spreading dust particles over PV module, decreasing the incident solar radiation. [50,51,52]

Since FPV’s is a new and modern research topic in the field of renewable energy and a lot of research has been carried out already. It is of vital significance to research the FPV system in such a context to encourage countries to opt for such technology and to keep updated in this field especially the developing ones. However, due to the high cost involved it is not easy to conduct research, most of the existing research discusses the system of kilowatts on a water body which requires significant time and funding. It would be of interest to develop a small-scale floating PV test bench as a step towards assessing FPV’s potential and analyzing the effect of environmental and climatic conditions of a particular location on the performance of FPV’s. Such a step would enable a pathway towards large-scale research. As FPV’s performance is affected by climatic conditions, a small-scale test bench would be of vital importance to analyze the performance of FPV’s at different locations. A study conducted revealed that the FPV system as compared to the on-ground PV system gained energy yield based on cooling effect up to 6% in Singapore and 3% in the Netherlands [53]. Azran Abdul Majid conducted an experimental study on FPV’s using an 80 $W_{p\ PV}$ panel in a pond simulator. The entire system has not been presented and the proposed design does not completely cover an actual FPV test bench [54]. Another study was conducted on an artificial pond using a 250 W_p PV panel to analyze its performance and comparison with a ground system [18]. Liu [55] developed a 1 MWp testbed in Singapore to study environmental and performance analysis. But no detail of system development has been presented. However, El Hammoumi [52] has conducted a study on a home-based FPV test bench. Test bench design and data logger details have been presented in detail. The study is based on Morocco's climatic conditions. The research concluded the performance of the FPV system under different tilt angles and measurement of PV panel rear temperature and water temperature. According to the study FPV provides better energy generation at a 30-degree tilt angle under Morocco climatic conditions. The research presented incorporates a study of evaporation and humidity, along with a thermal and electrical performance study of the FPV system and its comparison with the OPV system. The proposed testbench consists of identical FPV and OPV with both mono and polycrystalline panels of the same capacity. The proposed system is designed in such a way to have varying tilt angles, providing us the opportunity to study performance and environmental impacts on different tilt angles. One should consider that there is no research work being done on a test bench in Pakistan to assess the FPV system potential. Research conducted is distinctive as no test bench incorporates the study of the performance of both mono and polycrystalline FPV and comparison with OPV. Moreover, the test bench incorporates a fully automated measuring station to measure all the parameters required for analysis which has never been proposed for the FPV test bench. Implementing FPV's like a power generation source seems to be a great opportunity for Pakistan.

2.9 Related Work

Summary of related studies are presented in table 2.1.

Table 2.1 Summary of previous studies

Hammoumi et al. [52]	Morocco	Design and construction of a test bench to investigate the potential of floating PV power plant	Experimental study has been conducted on a small scale FPV system under Moroccan environmental conditions. The study concludes that FPV module are around 2.7 °C lower as compared to the OPV modules and produce around 2.33% more energy per day. The study also states that FPV system generates 43.5% more energy at optimal tilt angle as compared to 0 degree
Liu et al. [61]	China	Power Generation Efficiency and Prospects of Floating Photovoltaic Systems	A 3d finite analysis model has been implemented to study the potential of FPV system in China. The study concludes that FPV system can provide 2% more energy efficiency as compared to OPV
Majid et al. [54]	Malaysia	Study on performance of 80 watt floating photovoltaic panel	A two-hour experiment has been conducted on a small scall setup. Results show that as heat transfer from PV panel to the pond simulator, temperature of FPV module decrease as compared to the OPV and hence efficiency increase by around 15%. The study also concludes that the best tilt angle for the FPV system is equal to latitude but the max heat transfer take place at 0-degree tilt angle
Liu et al. [55]	Singapore	Field experience and performance	The study states that FPV system are 5-10 °C lower as compared to the OPV.

		analysis of floating PV technologies in the tropics	Due to this decrease in temperature energy yield increase. The study also concludes that the U-value for FPV is better than OPV systems
Maarten et al. [53]	Netherlands Singapore	The cooling effect of floating PV in two different climate zones: A comparison of field test data from the Netherlands and Singapore	The research presented is based on fields tests located in two different climatic zones, Singapore, and Netherlands. FPV system in Netherlands showed 3.2 °C and in Singapore 14.5 °C temperature difference as compared to the OPV system. There was an increase of heat loss coefficient of FPV system up to 22 W/m2K as compared to the OPV. Overall FPV system in Netherlands is 3% more energy efficient and around 6% in Singapore as compared to OPV.
Osama et al. [62]	Egypt	Design and construction of a test bench to investigate the potential of novel partially submerged PV system	Performance evaluation of partially submerged PV system (PSPV) has been studied in comparison with OPV. Results indicate that PSPV produce around 18% more electricity per day by submerging 10cm of PV length as compared to OPV
Qasim et al. [63]	Jordan	Floating PV; an assessment of water quality and evaporation reduction in semi-arid regions	The study states that FPV system has little advantage over land-based PV system power generation, but the due to the limited data collection the results cannot be statistically verified. However, FPV Mono crystalline panel showed higher power production while FPV poly panel showed the opposite result as compared to land-based system.
Leonardo et al. [64]	Spain	Energy and economic assessment of floating photovoltaics in Spanish reservoirs: cost competitiveness and the role of temperature	Results indicate that FPV electrical behaviour improves due the lower PV panel temperature. For FPV systems U-value is found out to be 56 W/m2K which is 2 times of that considered for OPV. The maximum U-value for the FPV system is found out to be 71 W/m2K as FPV modules have direct contact with water.
Goswami et al. [65]	India	Degradation analysis and the impacts on feasibility study of floating solar photovoltaic systems	Performance of FPV system as compared to OPV system is determined by conducting a small experiment. The data was logged manually. The study shows that due to low FPV temperature energy efficiency increased by 2%. Study also shows that degradation rate of FPV is 1.18% and that for OPV is 1.07%.

Summary

The main limitation of using PV power technology is the extensive land use: due to low PV panel efficiency, a large surface area of land is required. The Floating Photovoltaic System (FPV) appears to be the most promising option for rapid expansion of this technology. When compared to on-ground or roof-based PV systems, FPVs benefit from natural cooling from water basins. FPV systems reduce water evaporation from a body of water, thus providing a solution to water scarcity. The performance of an FPV system is determined by meteorological conditions; increasing relative humidity and wind speed have a negative impact on FPV energy generation. A FPV test bench is required to investigate the feasibility of an FPV system in a specific location. The presented research includes an evaporation and humidity study, as well as a thermal and electrical performance study of the FPV system and its comparison with the OPV system. The proposed testbench consists of identical FPV and OPV with the same nominal capacity of mono and polycrystalline panels. The proposed system is designed to have varying tilt angles, allowing us to study performance and environmental impacts on different tilt angles.

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Chapter 3: Research Methodology

3.1 Testbench and its Targets

A critical analysis and comparison are required between the Floating PV system (FPV) and On-Ground System (OPV), to compare and test the efficiency and benefits of the system. To investigate, a test bench is proposed consisting of OPV and FPV system along with a data measuring station. Targets of the proposed test bench are demonstrated in Figure 3.1. OPV system is installed on the rooftop while the FPV system is deployed on the pond simulator. The measuring station is developed consisting of several measuring sensors and instruments to measure the metrological parameters (ambient temperature, relative humidity impact on photovoltaic cells performance, water temperature), electrical parameters (current, voltage, and power), and PV modules temperature that is used in the test bench. Also, a tier 1 metrological station is used to measure solar radiation, wind speed, ambient temperature, and relative humidity. Therefore, the test bench is experimentally tested and analyzed for the evaluation of electrical performances (energy generation and efficiency) and thermal performances (module temperatures), and effects of metrological parameters on the FPV system as compared to the OPV. System integrates both mono and polycrystalline PV panels of same nominal capacity. Additionally, FPV and OPV system is tested under different tilt angles along with the study of evaporation in different situations (fully exposed, partially covered and fully covered).

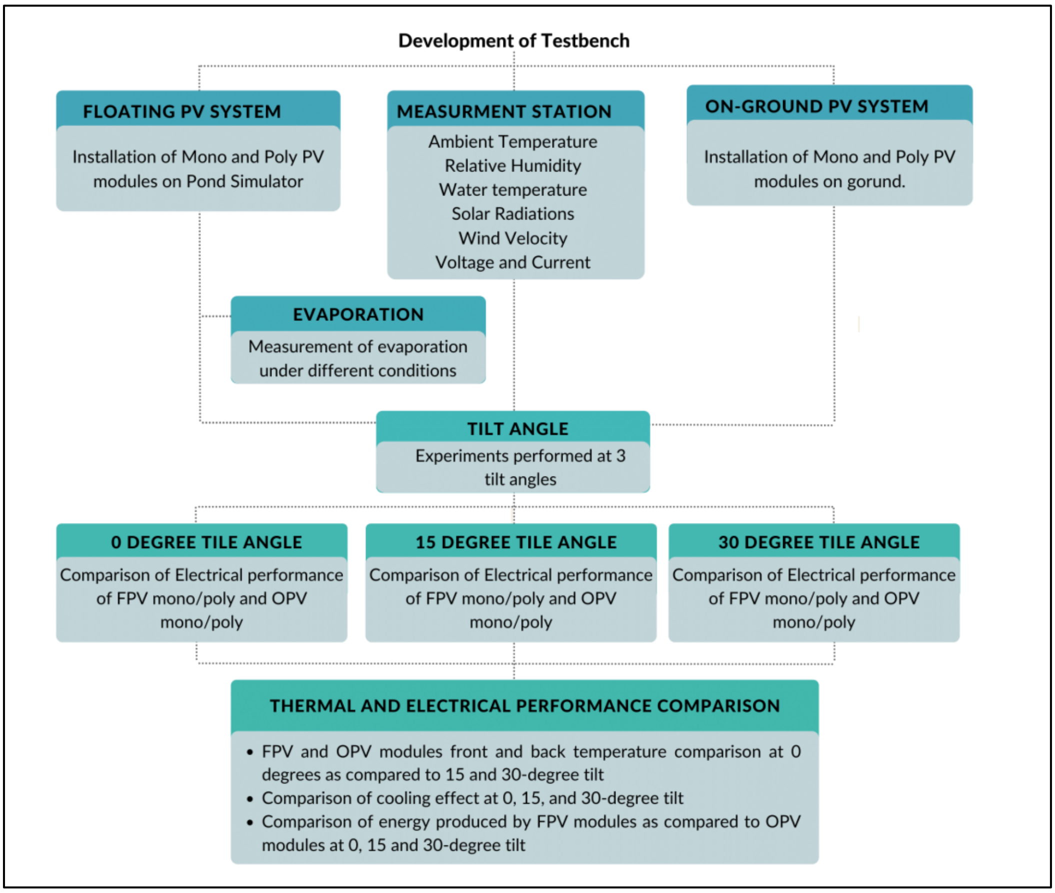


Figure 3.1: Outline of the Test Bench and its Targets

3.2 Proposed FPV System Design

FPV test bench is composed of supporting units, floating structure, and 2 PV panels, mono, and polycrystalline to generate electricity. Along with a measuring station to gather the data for system analysis. The floating structure is made of aluminum with the strength to bear the load of 2 PV panels. 6 polyethylene cans bear the load of the floating structure and play the role of floating units. The floating structure used to fix the PV panels is designed in such a way to get the varying tilt angle from 0^o to 70^o. A pond simulator (PVC water basin) of dimension 9.5ft x 6.5ft is used to install the FPV system. The data logger was enclosed in a waterproof box and fixed on the floating structure. Reference OPV system had a similar design except for the floating units and was placed on the rooftop. Figure 3.2 represents the real configuration of the test bench.

Figure 3.2: Configuration of FPV and OPV system

3.3 Description and experimental setup

The experimental setup of the proposed test bench is represented in Figure 3.3. Both FPV and OPV system contains 2 PV panels, monocrystalline and polycrystalline PV panel having dimensions of 2.5ft x2.5ft and 3.5ft x 2ft. All the panels used are of 80W at STC (standard test conditions) having the same electrical characteristics as shown in Table 3.1. PV panels of both systems are separately connected to the charge controller which charges the same battery specified for the FPV and OPV systems. The voltage sensor (0-25V) and Current sensor (ACS712 20A) are connected in the circuit of each panel to measure the power produced by PV panels. Thermocouples (DS18b20) are attached to the front and rear sides of PV panels to measure the panel temperatures and are also used to measure the water temperature. Thermal imaging is also used to measure the temperature of PV panels. DHT 11 sensor is used to measure the relative humidity and ambient temperature above FPV and OPV systems. All these sensors are connected to the acquisition board (Arduino UNO) for real-time data collection and data after every 30 secs is stored on an SD card in an excel file as shown in Figure 3.5. Moreover, the Real-Time Clock module (RTC) is used to measure the time of data acquisition. A separate data acquisition board is developed for each PV panel, Table 3.2 represents details of all the sensors and devices used. Data of horizontal solar radiation and wind speed is collected from tier 1 metrological weather station which is present on the same rooftop and is shown in Figure 3.4.

FPV structure is moored with the help of cables to maintain the position in the southern direction (optimal direction in Pakistan). As mentioned, this paper aims to study evaporation from the FPV pond simulator under different configurations, no cover, partially covered and fully covered. And to analyze the performance and environmental impact on FPV and OPV systems at different tilt angles, from 0^o-30^o. All tests are performed for 3 days under similar environmental conditions for better data acquisition and results.

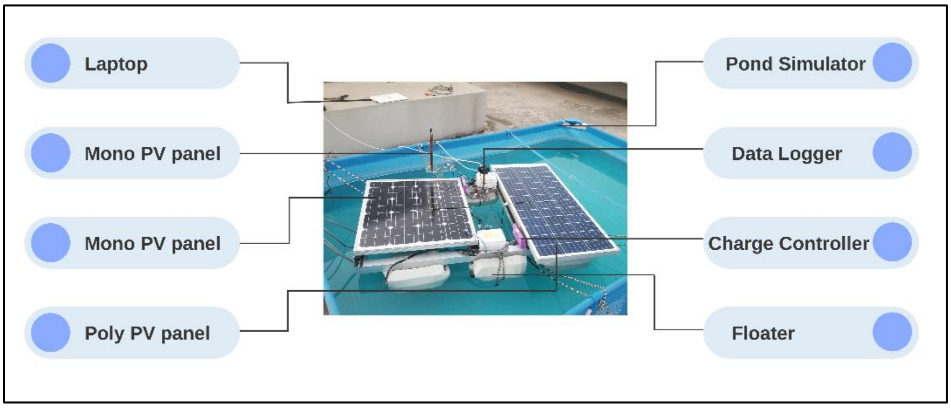


Figure 3.3: Experimental setup of proposed FPV Test Bench

Figure 3.4: Tier 1 Metrological Station Located at Nust

Table 3.1: Electrical Characteristics of PV Panels

PV Panel Electrical Characteristics	
Characteristic	**Value**
Maximum Power	80 W
Maximum Power Current	18.0 V
Maximum Power Voltage	4.45 A
Short Circuit Current	21.6 V
Open Circuit Voltage	4.81 A

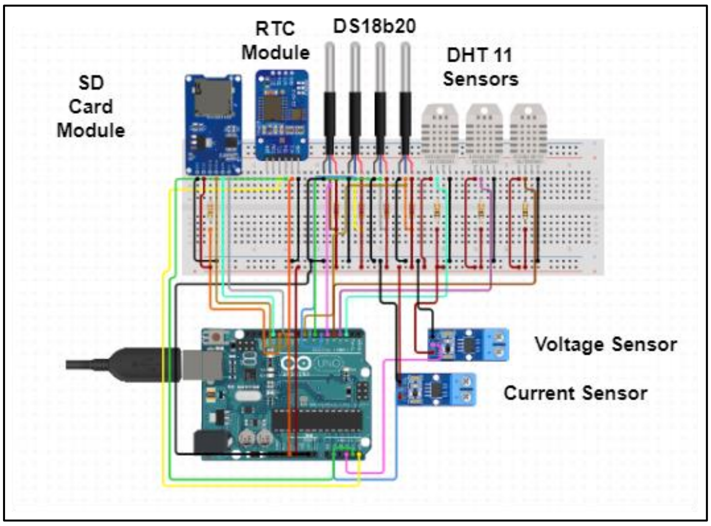


Figure 3.5: Circuit Diagram of a Data Acquisition System

Table 3.2: Components of Measuring Station

Components of Measuring Station	
Component	**Description**
Arduino Uno	It is used to acquire real-time data from multiple sensors and store them in an SD card along with the data acquisition time.
Current Sensor (20A)	It is used to measure the current produced by the PV panel.
Voltage Sensor (0-25V)	It is used to measure the voltage produced by the PV panel.
Thermocouple (DS18B20)	4 thermocouples are integrated to measure the front and back temperatures of the PV panel and to measure ambient and water temperature.
DHT 11 Sensor	3 sensors are used to measure ambient temperature and relative humidity.
Real-Time Current Module (RTC)	It is used to log the time against the data acquired.
Pyranometer	It is used to measure horizontal solar radiation.
Anemometer	It is used to measure wind speed.

Summary

To compare and test the efficiency and benefits of the system, a critical analysis and comparison of the Floating PV system (FPV) and On-Ground System (OPV) are required. To investigate, a test bench comprised of an OPV and FPV system, as well as a data measuring station, is proposed. The measuring station is built with several measuring sensors and instruments to measure the metrological parameters, electrical parameters, and temperature of the PV modules used in the test bench. The FPV test bench is made up of supporting units, a floating structure, and two monocrystalline and polycrystalline PV panels. It is designed in a such a way to have varying tilt angles of PV modules. The FPV system was installed in a pond simulator (PVC water basin). The purpose of this paper is to investigate evaporation from the FPV pond simulator in three different configurations: no cover, partially covered, and fully covered. And to investigate the performance and environmental impact of FPV and OPV systems at various tilt angles ranging from 0^o to 30^o. For better data acquisition, all tests are carried out over a three-day period in similar environmental conditions.

Chapter 4: Results and Discussion

This chapter is divided into 6 sections. In the first section results of evaporation has been discussed. In the second section results of 0-degree experiment has been discussed along with the discussion on weather data, thermal behavior of PV modules, thermal imaging, and power conversion in sub sections. Similarly, in the third and fourth section results of 15- and 30-degree experiment has been presented and discussed. In the fifth section thermal comparison between different tilt angles has been done. And in the last section power and optimal tilt angle has been discussed

4.1 Evaporation

Experiments have been performed for 3 days for each test. To observe the evaporation from the pond simulator when it is fully exposed, partially covered, and fully covered (90%), Figure 4.1 represents a fully open experimental setup while Figure 4.2 and Figure 4.3 show the configuration of partially and fully covered evaporation test.

Figure 4.1: Fully Open Evaporation Test

Figure 4.2: Partially Covered Evaporation Test

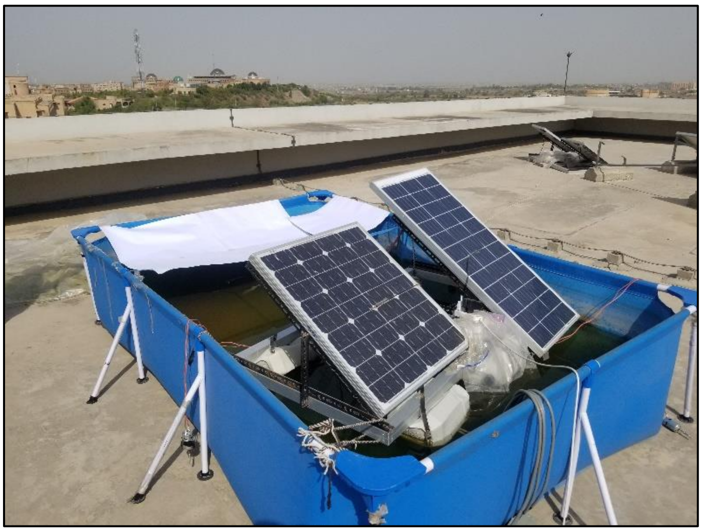


Figure 4.3: Fully Covered Evaporation Test

In all three tests, weather conditions were almost steady with little variations as shown in Figure 4.4,Figure 4.5 and Figure 4.6. For each experiment, pond simulator contained 2603.754 liters of water. When the pond simulator was fully opened to the sky, it was observed that 199.11 liters of water evaporated while 168 liters of water and 150 liters of water evaporated when it was partially covered and fully covered. 17% evaporation was reduced by covering the pond simulator partially while 28% evaporation was reduced by covering the simulator fully. Water temperature in the case of a fully opened pond simulator is equal to the ambient temperature as shown in Figure 4.4. In the case of a partially covered pond simulator around 4-5°C temperature difference is observed between ambient and water temperature while in the fully covered pond simulator 10-11°C temperature difference can be seen in Figure 4.5 and Figure 4.6.

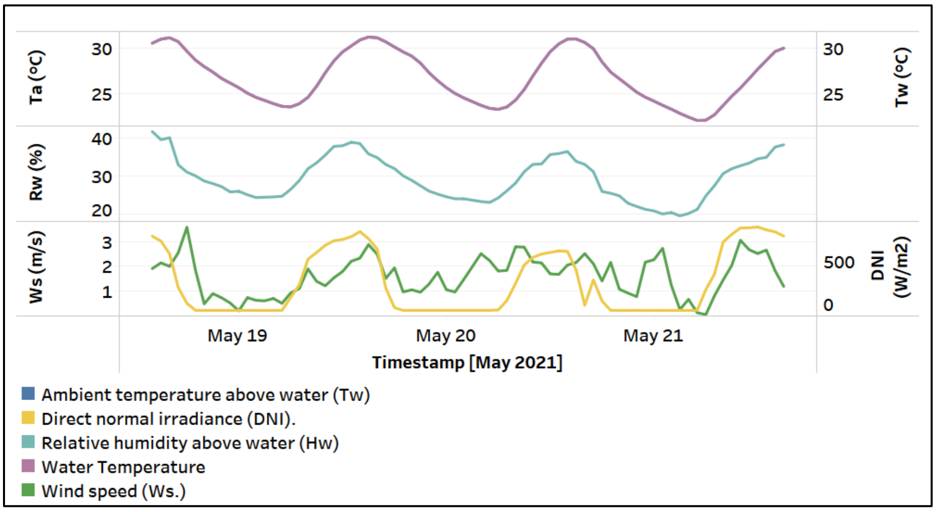


Figure 4.4: Fully Open Pond Simulator Parameters

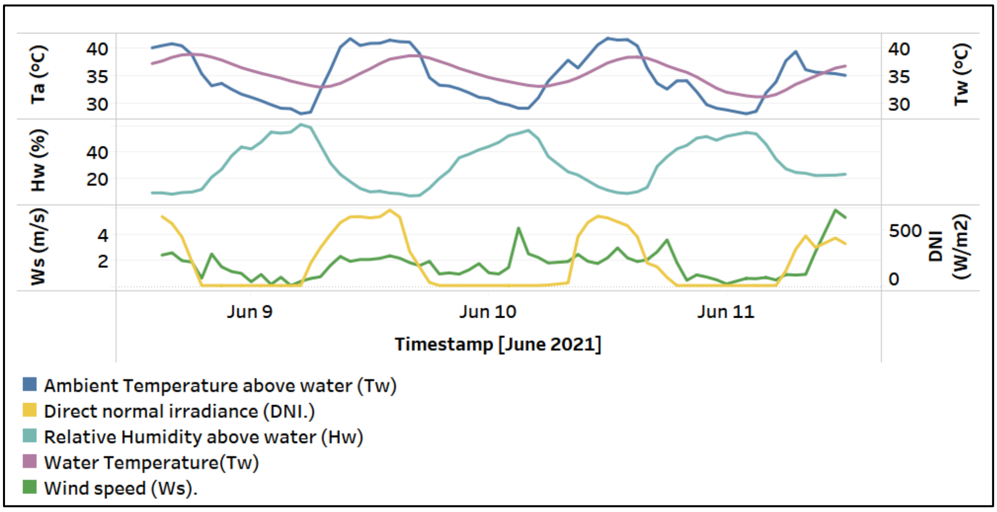


Figure 4.5: Partially covered Pond Simulator Parameters

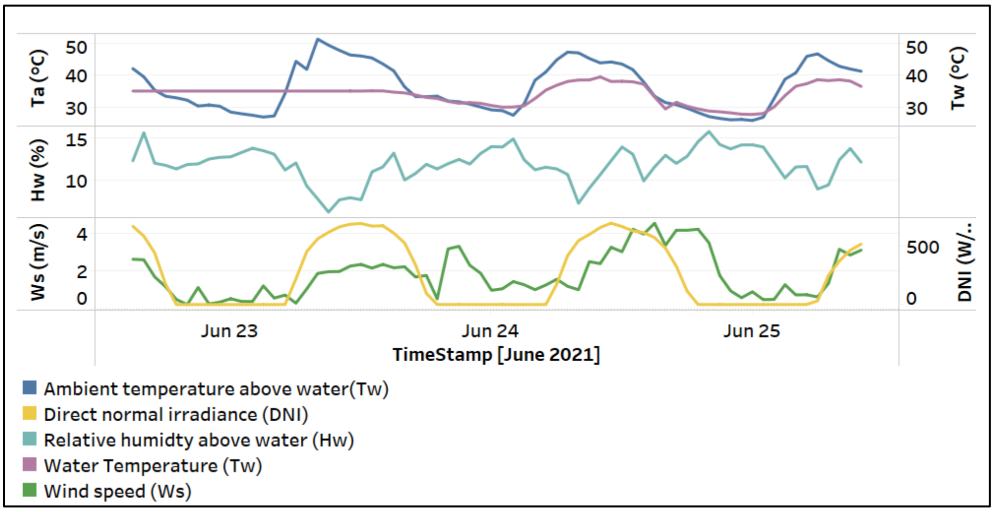


Figure 4.6: Fully covered Pond Simulator Parameters

Evaporation from a water body is not simple as it depends on many factors such as solar radiation, water thermal energy, relative humidity, wind speed, and water thermal equilibrium. Similar results have been found previous studies as discussed in literature review.

4.2 0 Degree Tilt Angle

The experimental test has been performed for 3 days: from June 8th, 2021, to June 10th, 2021 in NUST, Islamabad. Data after every 30 secs has been logged using a data logger. FPV experimental setup is shown in Figure 4.7(A) and OPV experimental setup is shown in Figure 4.7(B)

4.7 (A)

4.7 (B)

Figure 4.7: 0 Degree Experimental Setup

4.2.1 Weather data

The weather during the time was steady, with a maximum of 634 W/m^2 of solar radiation per day as shown in Figure 4.8. Figure 4.9Figure 4.10 represent recorded trends of ambient temperature and relative humidity above FPV and OPV system installed at 0 degrees. The maximum ambient temperature above water reached a value of 43.4°C while it reached a maximum value of 53°C above the OPV system. Maximum humidity above water was recorded to be 62.9% while above OPV system it reached 87.1 %. Similarly, the minimum temperature and relative humidity recorded above the FPV system were 27.9°C and 5.8%. And minimum temperature and humidity above the OPV system were recorded to be 28°C and 14% respectively. The maximum water temperature recorded in 3 days was 39°C and the minimum water temperature recorded was 31°C.

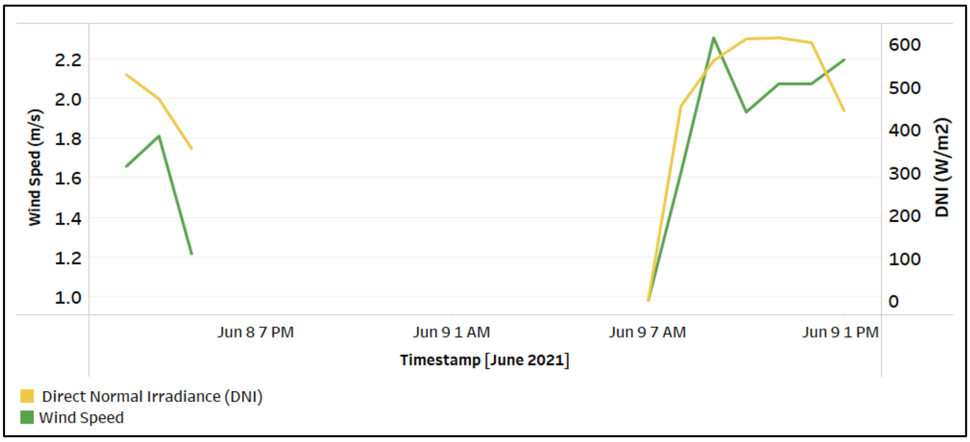


Figure 4.8: Solar radiation and Wind Speed Trends - 0 Degree Experiment

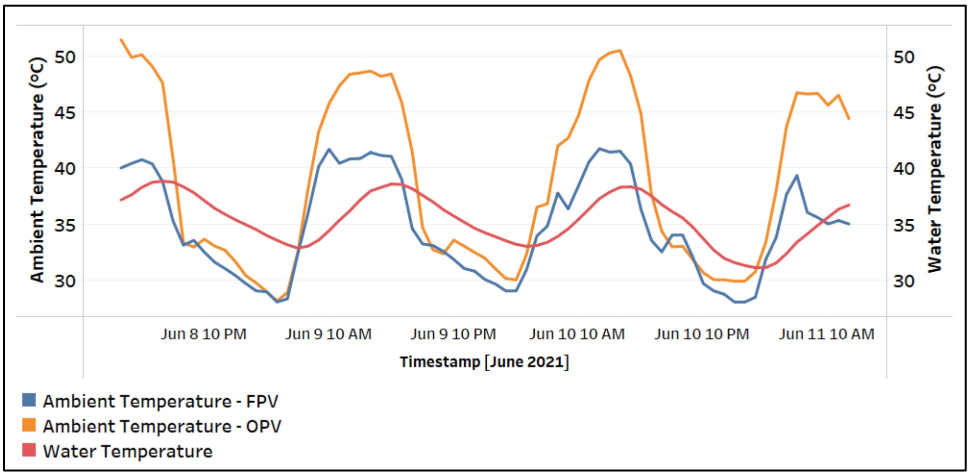


Figure 4.9: Ambient and Water Temperature Trends - 0 Degree Experiment

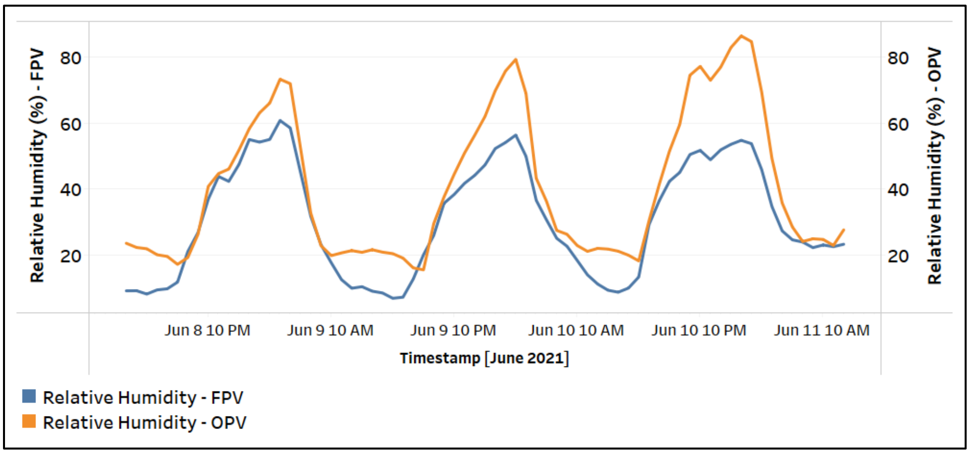


Figure 4.10: Relative Humidity Trends - 0 Degree Experiment

Trends shown in Figure 4.9Figure 4.10 show that during the daytime, the temperature above the OPV system is greater by 9-10°C as compared to the FPV system. Similarly, relative humidity deviates by 11-12% during the daytime. At nighttime ambient temperature shows similar trends while relative humidity above OPV system is 11-12% more as compared to relative humidity above FPV system. Mostly, water temperature is 4-5°C lower than ambient temperature (FPV) which is required to create the cooling effect for better FPV energy generation. The ambient temperature above the FPV system is lower as water provides cooling, lowering the air temperature. And as cold air holds less vapor, relative humidity decrease. Research states that relative humidity affects incoming solar radiation by reducing the solar radiation as already discussed in literature review.

4.2.2 Thermal Behavior of PV Modules

During the study, the thermal behavior of PV modules has also been observed. The temperature of the rear and front sides has been measured using the thermocouple (DS18B20). This will provide us a better understanding of the cooling effect and thermal behavior of modules. Rear and front temperatures of mono and polycrystalline PV modules were almost the same in the case of FPV and OPV systems which have been averaged. Figure 4.11 represents the rear and front side temperature trends of FPV modules and OPV modules along with water temperature trends. On day 1, during the peak time of solar radiation around 1:00 – 2:00 Pm. FPV module front temperature reached a maximum temperature of 61°C, while the front of the OPV module reached a maximum temperature of 63.3°C having a temperature difference of around 2.3°C between the front of OPV and FPV modules. Similarly, the back of the FPV module reached a maximum temperature of 53.8°C while the back of the OPV module reached a maximum temperature of 63.5°C having a temperature deviation of 9.7°C between the rear side of the two systems. During this period, the maximum water temperature observed was 37°C. On days 2 and 3 between 1:00 – 2:00 pm, the maximum front temperature deviation between the front of the FPV and OPV system was 3.3°C and 3.4°C. And maximum rear temperature deviation between the rear sides was 10.2°C and 10.8°C respectively. While maximum water temperature was 38°C and 36°C. This represents the cooling effect of water provided by the water surface, hence contributing towards lower PV module temperature and better performance. Overall, it is observed that the back of the FPV system module is 10-11°C lower than the back of the OPV system module, and the fronts of each system show only a deviation of 2-4°C. Obtained results are also verified by the studies mentioned in literature review.

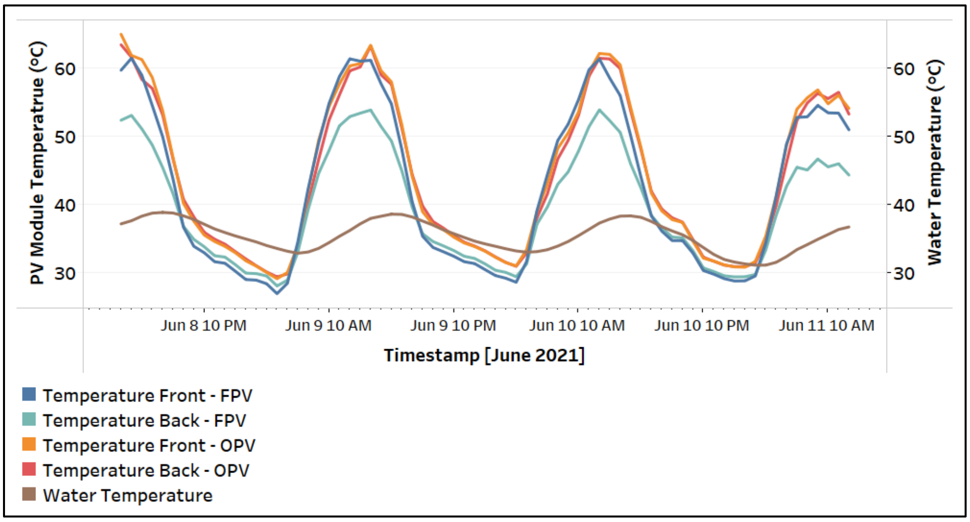
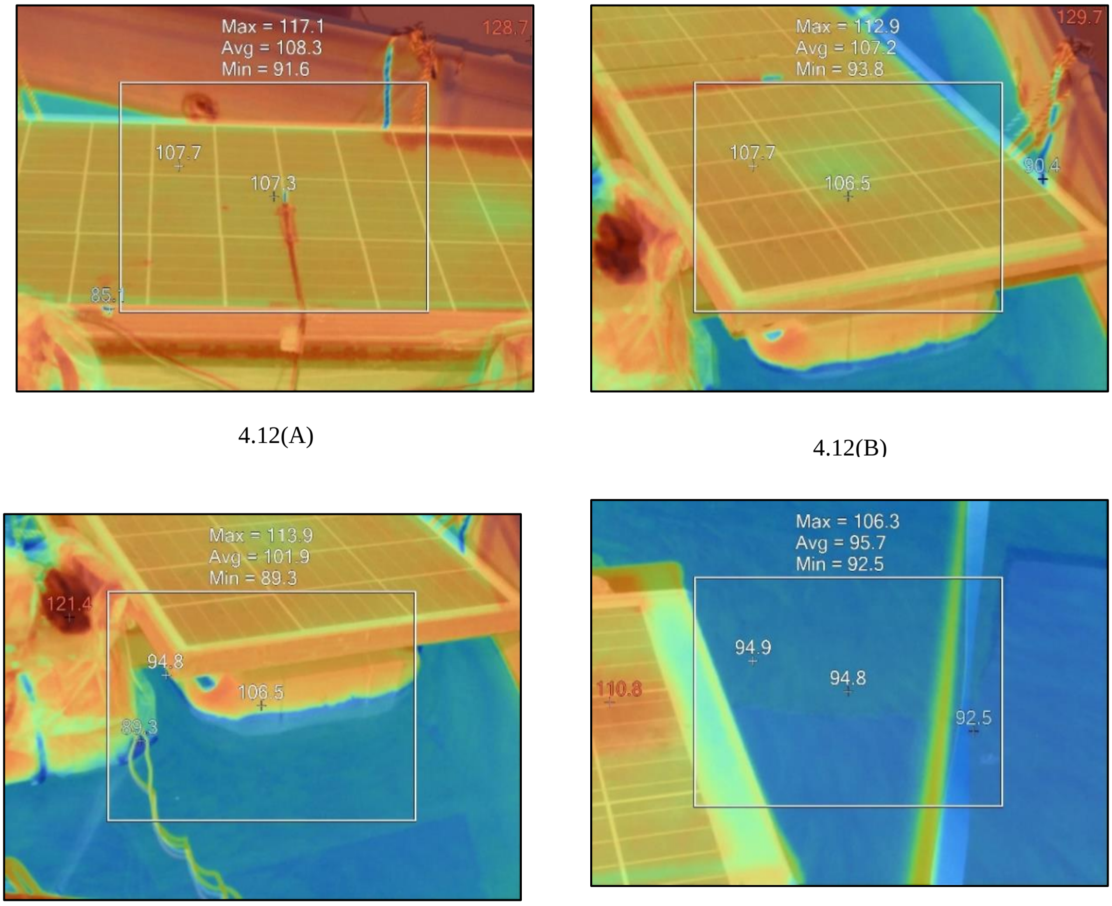


Figure 4.11: FPV and OPV Modules Temperature Trends – 0 Degree Experiment

4.2.3 Thermal Imaging

Thermal imagining is also done to study the thermal behavior of PV modules. All images are taken on the last day of the experiment at 1:00 pm. Figure 4.12 represents thermal imaging of the FPV module at 0 degrees tilt. Figure 4.12(A and B) represent thermal imagining of the front side of the FPV module. The difference between temperature in the center and bottom of the PV module is not significant. In the center of the PV module temperature is 41.8°C while at the bottom it is 41.3°C. The frame supporting the FPV modules also has the same temperature of 41.3°C, and water has a comparatively less temperature of 34.8°C. As shown in Figure 4.12(C and D).



4.12(A)

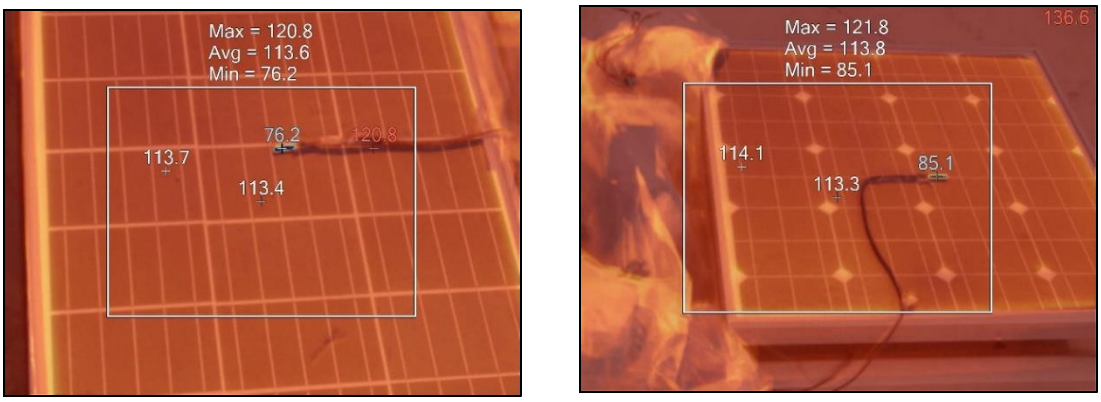
4.12(B)

4.12(C)

4.12(D)

Figure 4.12: Thermal Imaging of FPV Modules - 0 Degree Experiment 4.12(A) Thermal Imaging of Mid of FPV Module, 4.12(B) Thermal Imagining of Bottom of FPV Module, 4.12(C) Thermal Imagining of Frame of FPV Module, 4.12(D) Thermal Imagining of Water in Pond Simulator

Similarly, thermal imagining of OPV modules has been done to study their thermal behavior as shown in Figure 4.13. Figure 4.13 (A and B) represent that the OPV module has a temperature of 45.2°C while roof temperature is about 58.1°C. OPV and FPV modules have a front thermal difference of 3.9°C. Around 10-11°C module back temperature difference has been seen in Figure 4.11, this is due to the base temperature of FPV and OPV system. In the FPV system base, water temperature and OPV system base roof have a temperature difference of 23.3°C, hence causing a back temperature difference in the systems.



4.13 (A) 4.13 (B)

Figure 4.13: Thermal Imaging of OPV Modules - 0 Degree Experiment 4.13(A) Thermal Imagining of Center of OPV Module, 4.13(B) Thermal Imagining of Center of OPV Module and Roof

4.2.4 Power Conversion

The voltage and current of each panel are measured by connecting voltage and current sensors in the circuit. It is observed that there is more deviation in voltage as compared to the current due to a change in PV panel temperature. Trends of power produced are shown in Figure 4.14. Maximum values of power produced are observed in between 12-1 Pm. During day 1 FPV mono produced 79.98W, FPV poly produced 74W, OPV mono produced 58.5W and OPV poly produced 54.5W respectively. During day 2 and day 3 in between 12-1 pm, FPV mono produced 71W and 77W, FPV poly produced 71W and 60W, OPV mono produced 59W and 40W while OPV poly produced 55W and 36W. From the Figure 4.14, it can be noted that trends of power produced by FPV mono module are highest followed by FPV poly module, OPV mono module, and OPV poly module. The greater efficiency of the FPV system is because the water body provided the cooling effect and the ambient temperature and relative humidity above the FPV system is less as compared to the OPV system as shown in Figure 4.9Figure 4.10. While FPV module temperature decrease due to cooling effect, OPV module temperature increase due to increased temperature of the rooftop as shown in Figure 4.11 and Figure 4.13(B).

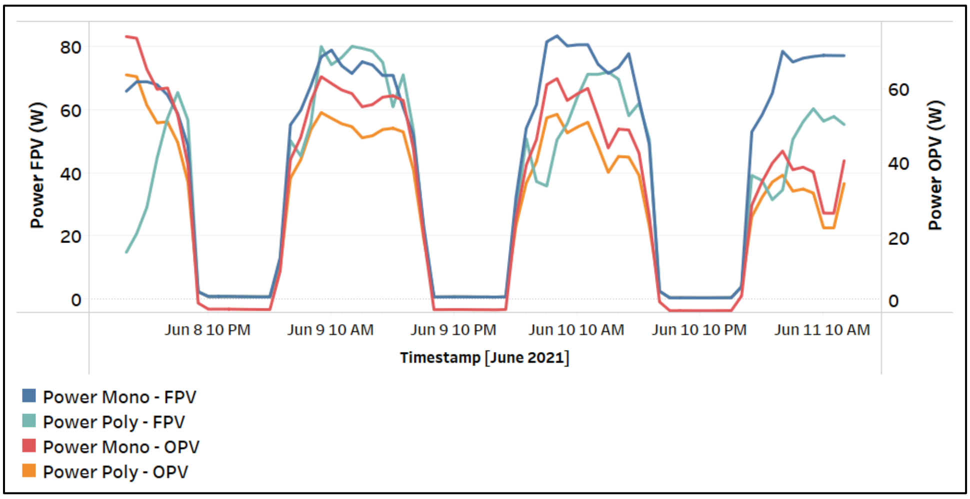


Figure 4.14: Trends of Power Production from FPV and OPV system - 0 Degree Experiment

4.3 15 Degree Tilt Ange

This experimental test has been performed for 3 days: from June 18th, 2021, to June 21st, 2021 in NUST, Islamabad. Data after every 30 secs have been logged using a data logger. FPV experimental setup is shown in Figure 4.15(A) and OPV experimental setup is shown in Figure 4.15 (B)

4.15 (A)

4.15 (B)

Figure 4.15: 15 Degree Experimental Setup

4.3.1 Weather data

The weather during the time was steady, with a maximum of 666 W/m^2 of solar radiation per day as shown in Figure 4.16. Figure 4.17 and Figure 4.18 represent recorded trends of ambient temperature and relative humidity above FPV and OPV system installed at 15 degrees. The maximum ambient temperature above water during the day reached a value of 44.8°C while it reached a maximum value of 55.5°C above the OPV system. Maximum humidity above water was recorded to be 54.4% while above the OPV system it reached 51% at nighttime. Similarly, the minimum temperature and relative humidity recorded above the FPV system were 25.3°C and 3%. And minimum temperature and humidity above the OPV system were recorded to be 26°C and 10% respectively.

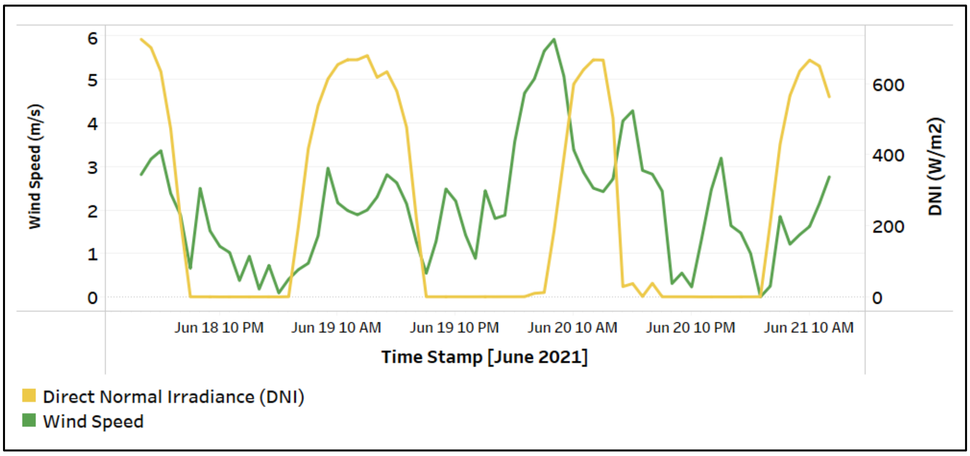


Figure 4.16: Solar radiation and Wind Speed Trends - 15 Degree Experiment

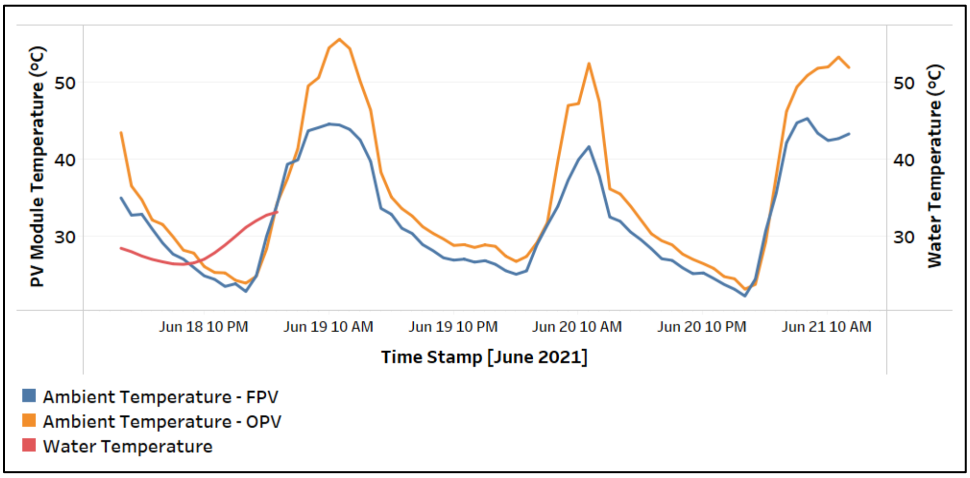


Figure 4.17: Ambient and Water Temperature Trends - 15 Degree Experiment

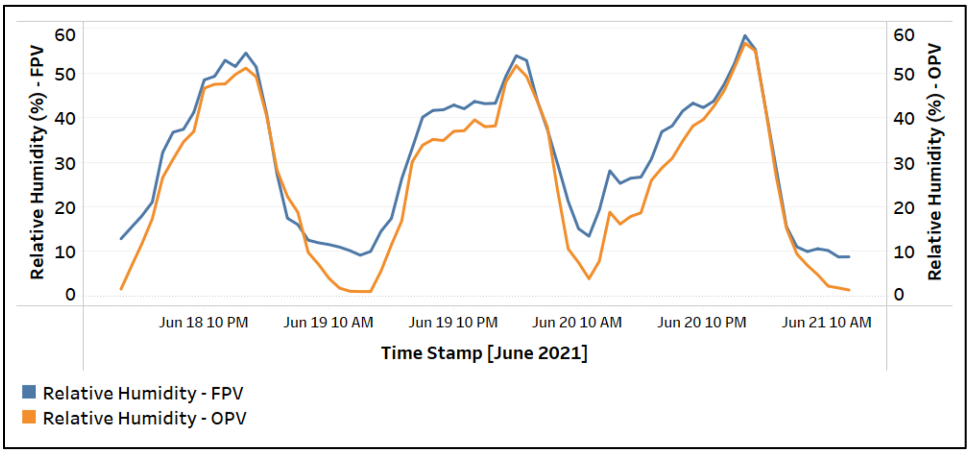


Figure 4.18: Relative Humidity Trends - 15 Degree Experiment

Trends shown in Figure 4.17 and Figure 4.18 show that during the daytime, the temperature above the OPV system is greater by 10-11°C as compared to the FPV system. Similarly, relative humidity deviates by 7-10% during the daytime. At nighttime ambient temperature and relative humidity shows similar trends. Mostly, water temperature is lower than ambient temperature (FPV) which is required to create the cooling effect for better FPV energy generation. The ambient temperature above the FPV system is lower as water provides cooling, lowering the air temperature. And as cold air holds less vapor, relative humidity decrease.

4.3.2 Thermal Behavior of PV Modules

During the study, the thermal behavior of PV modules has also been observed. The temperature of the rear and front sides has been measured using the thermocouple (DS18B20). This will provide us a better understanding of the cooling effect and thermal behavior of modules. Rear and front temperatures of mono and polycrystalline PV modules were almost the same in the case of FPV and OPV systems which have been averaged. Figure 4.19 represents the rear and front side temperature trends of FPV modules and OPV modules along with water temperature trends. On day 1, during the peak time of solar radiation around 1:00 – 2:00 Pm. FPV module front temperature reached a maximum temperature of 58.8°C, while the front of the OPV module reached a maximum temperature of 59.6°C having a temperature difference of around 0.8°C between the front of OPV and FPV modules. Similarly, the back of the FPV module reached a maximum temperature of 52.1°C while the back of the OPV module reached a maximum temperature of 60.7°C having a temperature deviation of 8.6°C between the rear side of the two systems. During this period, the maximum water temperature observed was 33°C. On days 2 and 3 between 1:00 – 2:00 Pm, the maximum front temperature deviation between the front of the FPV and OPV system was 0.3°C and 0.4°C. And maximum rear temperature deviation between the rear sides was 7.9°C and 8°C respectively. This represents the cooling effect of water provided by the water surface, hence contributing towards lower PV module temperature and better performance. Overall, it is observed that the back of the FPV system module is 7-9°C lower than the back of the OPV system module, and the fronts of each system show only a deviation of 0.3-1°C.

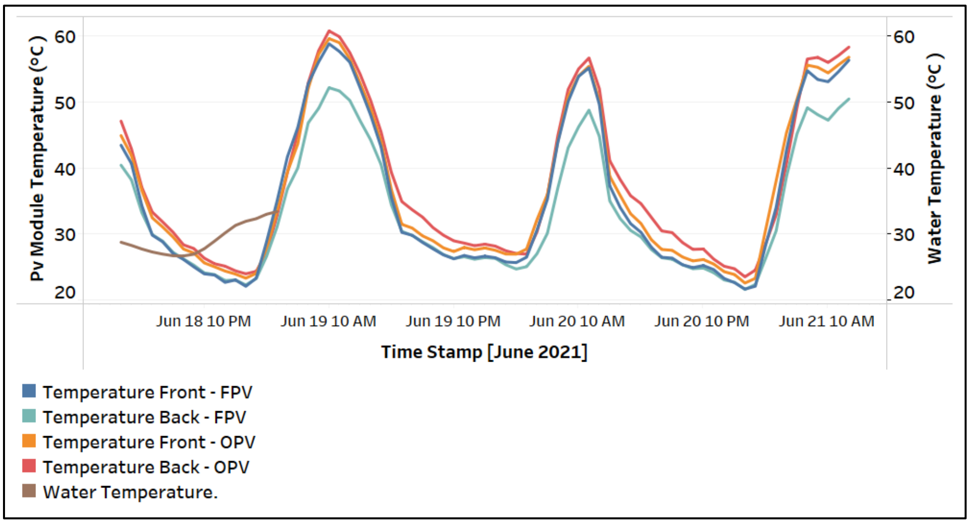
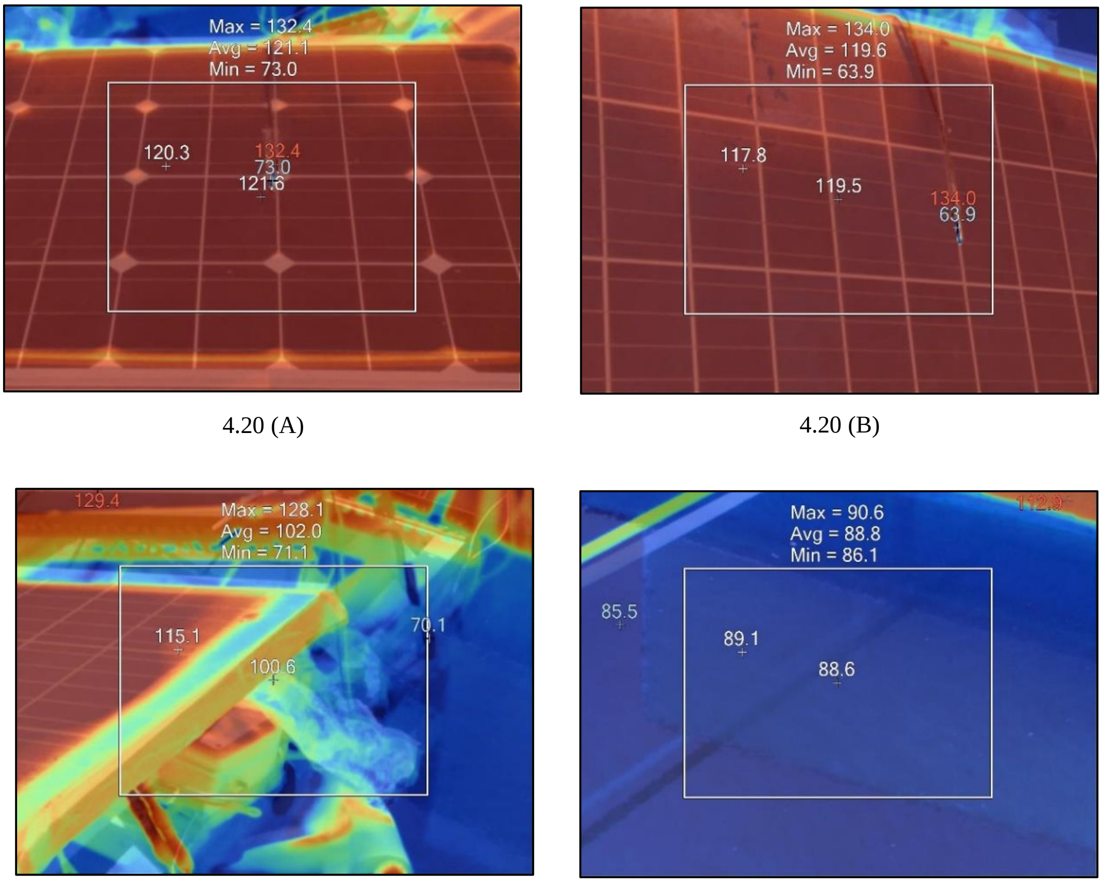


Figure 4.19: FPV and OPV Modules Temperature Trends – 15 Degree Experiment

4.3.3 Thermal Imaging

Thermal imagining has been done to study the thermal behavior of PV modules. All images are taken on the last day of the experiment at 1:00 Pm. Figure 4.20 represents thermal imaging of the FPV module at 15 degrees tilt. Figure 4.20 (A and B) represents thermal imagining of the front side of the FPV module. The difference between temperature in the center and bottom of the PV module is not significant. In the center of the PV module temperature is 49.4°C while at the bottom it is 48.3°C. The frame supporting the FPV modules also has the same temperature of 38°C, and water has comparatively less temperature of 31°C as shown in Figure 4.20 (C and D).

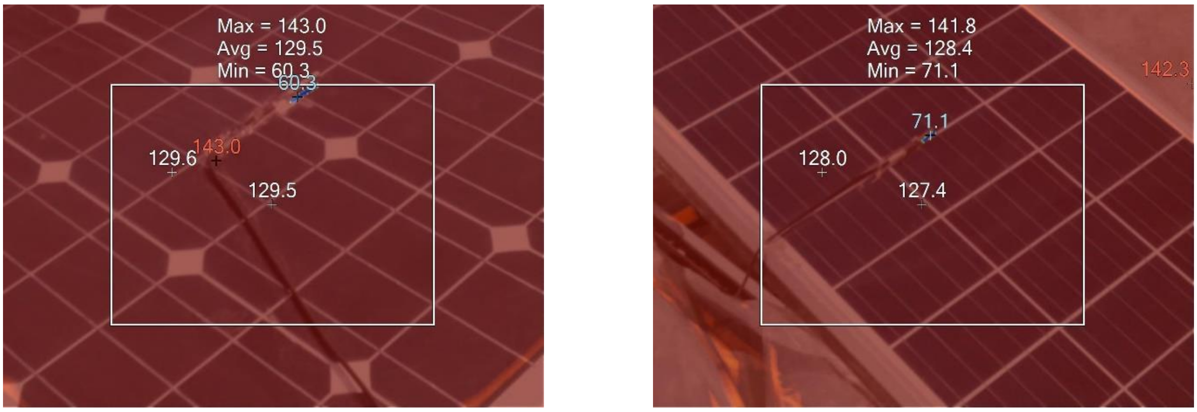


4.20 (A) 4.20 (B)

4.20 (C) 4.20 (D)

Figure 4.20: Thermal Imaging of FPV Modules - 15 Degree Experiment 4.20(A) Thermal Imaging of Mid of FPV Module, 4.20 (B) Thermal Imagining of Bottom of FPV Module, 4.20(C) Thermal Imagining of Frame of FPV Module, 4.20 (D) Thermal Imagining of Water in Pond Simulator

Similarly, thermal imagining of OPV modules has been done to study their thermal behavior as shown in Figure 4.21. Figure 4.21 (A and B) represent that the OPV module has a temperature of 53.8°C while roof temperature is about 61.1°C. OPV and FPV Modules have a front thermal difference of 4.4°C. Around 7-9°C back temperature difference has been seen in Figure 4.19, this is due to the base temperature of the FPV and OPV system. In the FPV system base, water temperature and OPV system base roof have a temperature difference of 30°C, hence causing back temperature difference in the systems.



4.21 (A)

4.21 (B)

Figure 4.21: Thermal Imaging of OPV Modules - 15 Degree Experiment
4.21 (A) Thermal Imagining of Center of OPV Module,
4.21 (B) Thermal Imagining of Center of OPV Module and Roof

4.3.4 Power Conversion

The voltage and current of each panel are measured by connecting voltage and current sensors in the circuit. It is observed that there is more deviation in voltage as compared to the current due to a change in PV panel temperature. Maximum values of power produced are observed in between 12-1 Pm as shown in Figure 4.22. During day 1 FPV mono produced 91.2W, FPV poly produced 85.4W, OPV mono produced 71.9W and OPV poly produced 68.6W respectively. During day 2 and day 3 in between 12-1 pm, FPV mono produced 86W and 82W, FPV poly produced 80W and 76W, OPV mono produced 76W and 58W while OPV poly produced 73W and 54W. From the Figure 4.22, it can be noted that trends of power produced by FPV mono module are highest followed by FPV poly module, OPV mono module, and OPV poly module respectively. The greater efficiency of the FPV system is because the water body provided the cooling effect and the ambient temperature and relative humidity above the FPV system is less as compared to the OPV system as shown in Figure 4.17Figure 4.18 and Figure 4.9. While FPV module temperature decrease due to cooling effect, OPV module temperature increase due to increased temperature of the rooftop as shown in Figure 4.19 and Figure 4.21(B).

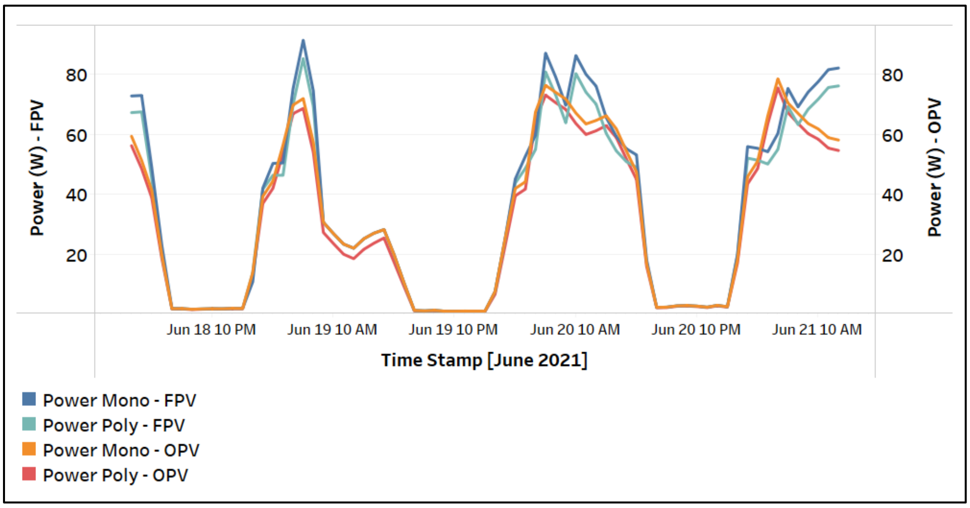


Figure 4.22: Trends of Power Production from FPV and OPV system - 15 Degree Experiment

4.4 30 Degree Tilt Angle

This experimental test has been performed for 3 days: from June 22nd, 2021, to June 25th, 2021 in NUST, Islamabad. Data after every 30 secs have been logged using a data logger. FPV experimental setup is shown in Figure 4.23(A) and OPV experimental setup is shown in Figure 4.23 (B)

4.23 (A)

4.23 (B)

Figure 4.23: 15 Degree Experimental Setup

4.4.1 Weather data

The weather during the time was steady, with a maximum of 691 W/m2 of solar radiation per day as shown in Figure 4.24. Figure 4.25Figure 4.26 represent recorded trends of ambient temperature and relative humidity above FPV and OPV system installed at 30 degrees. The maximum ambient temperature above water during the day reached a value of 51°C while it reached a maximum value of 58.5°C above the OPV system. Maximum humidity above water was recorded to be 16.4% while above the

OPV system it reached 37% at nighttime. Similarly, the minimum temperature and relative humidity recorded above the FPV system were 25.7°C and 6.9%. And minimum temperature and humidity above the OPV system were recorded to be 27°C and 6.7% respectively.

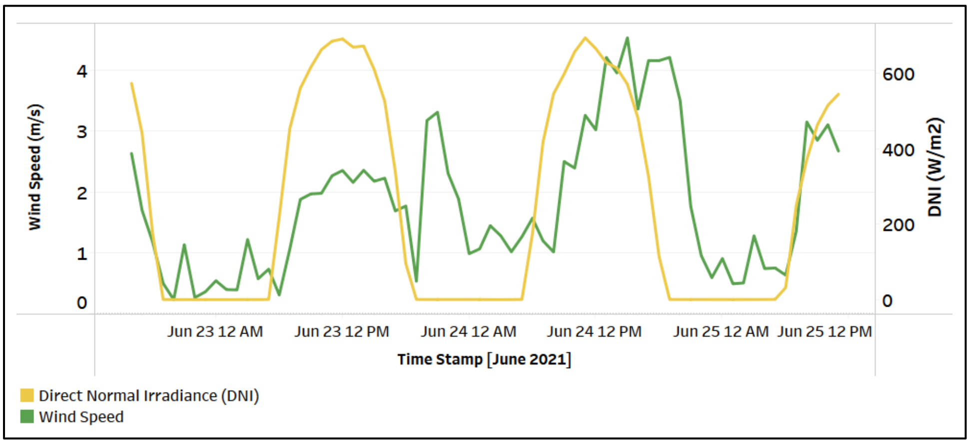


Figure 4.24: Solar radiation and Wind Speed Trends - 30 Degree Experiment

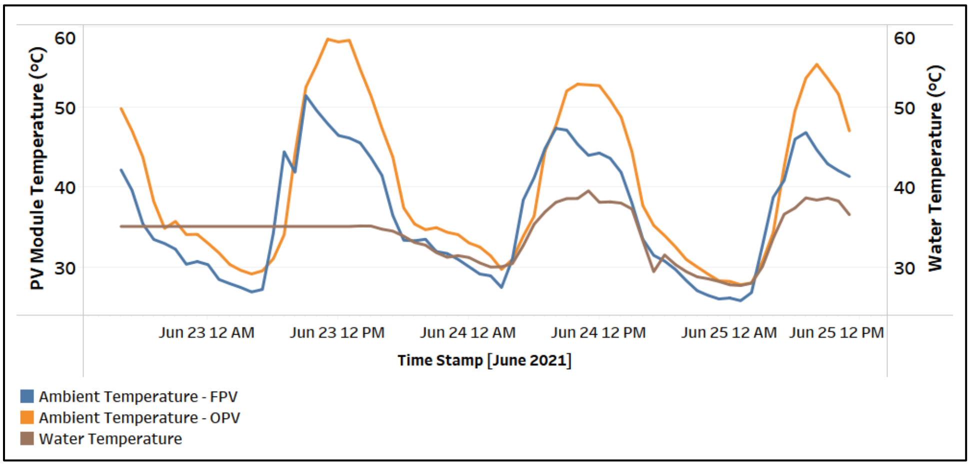


Figure 4.25: Ambient and Water Temperature Trends - 30 Degree Experiment

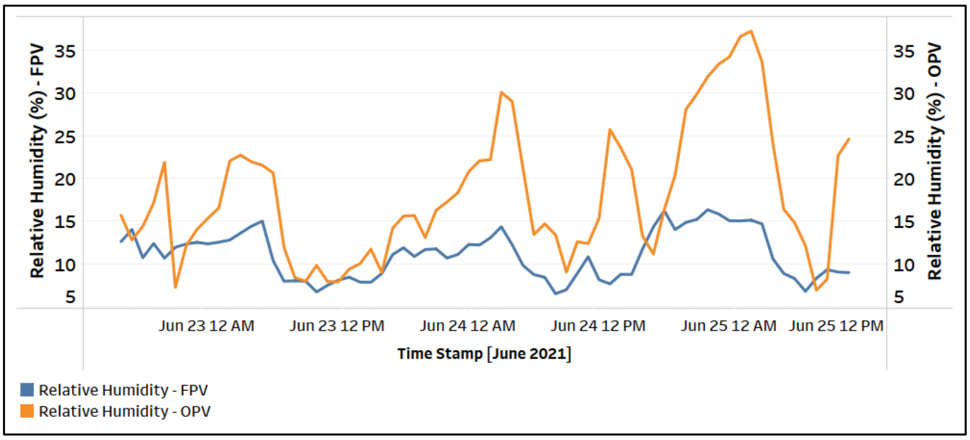


Figure 4.26: Relative Humidity Trends - 30 Degree Experiment

Trends shown in Figure 4.25 Figure 4.26 show that during the daytime, the temperature above the OPV system is greater by 8-12°C as compared to the FPV system. Similarly, relative humidity deviates by 3-5% during the daytime. At nighttime ambient temperature show similar trends while relative humidity above OPV system is 15-17% greater than FPV system. Mostly, water temperature is 5-6°C lower than ambient temperature (FPV) which is required to create the cooling effect for better FPV energy generation. The ambient temperature above the FPV system is lower as water provides cooling, lowering the air temperature. And as cold air holds less vapor, relative humidity decrease.

4.4.2 Thermal Behavior of PV Modules

During the study, the thermal behavior of PV modules has also been observed. The temperature of the rear and front sides has been measured using the thermocouple (DS18B20). This will provide us a better understanding of the cooling effect and thermal behavior of modules. Rear and front temperatures of mono and polycrystalline PV modules were almost the same in the case of FPV and OPV systems which have been averaged. Figure 4.27 represents the rear and front side temperature trends of FPV modules and OPV modules along with water temperature trends. On day 1, during the peak time of solar radiation around 1:00 – 2:00 Pm. FPV module front temperature reached a maximum temperature of 61.91°C, while the front of the OPV module reached a maximum temperature of 65.4°C having a temperature difference of around 3.5°C between the front of OPV and FPV modules. Similarly, the back of the FPV module reached a maximum temperature of 58.9°C while the back of the OPV module reached a maximum temperature of 65°C having a temperature deviation of 6.1°C between the rear side of the two systems. During this period, the maximum water temperature observed was 35°C. On days 2 and 3 between 1:00 – 2:00 Pm, the maximum front temperature deviation between the front of the FPV and OPV system was 3°C and 3.5°C. And maximum rear temperature deviation between the rear sides was 5.2°C and 4°C respectively. This represents the cooling effect of water provided by the water surface, hence contributing towards lower PV module temperature and better performance. Overall, it is observed that the back of the FPV system module is 4-6°C lower than the back of the OPV system module, and the fronts of each system show only a deviation of 3-3.5°C.

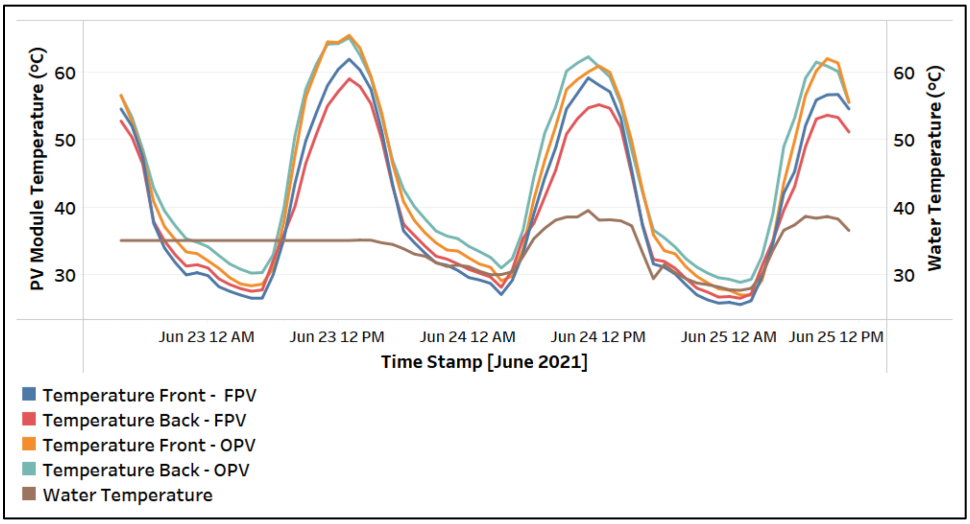
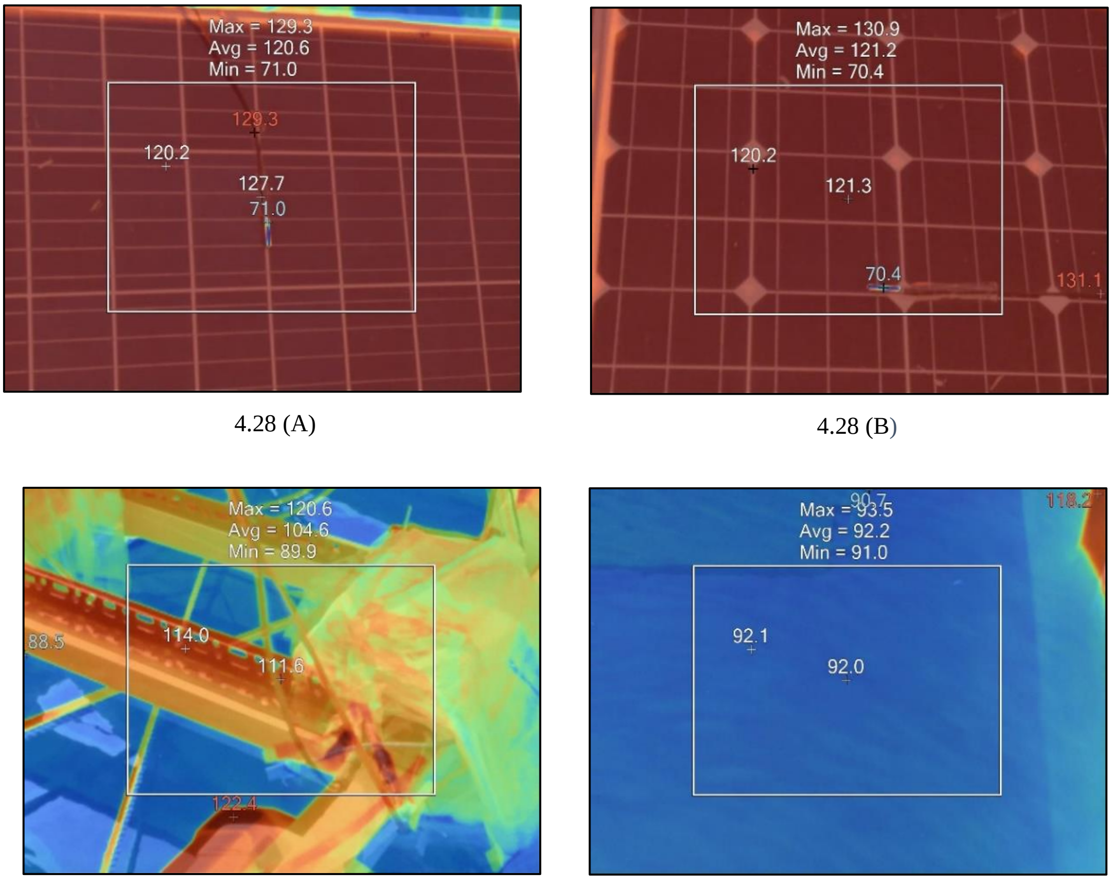


Figure 4.27: FPV and OPV Modules Temperature Trends – 30 Degree Experiment

4.4.3 Thermal Imagining

Thermal imagining has been done to study the thermal behavior of PV modules. All images are taken on the last day of the experiment at 1:00 Pm. Figure 4.28 represents thermal imaging of the FPV module at 30 degrees tilt. Figure 4.28 (A and B) represent thermal imagining of the front side of the FPV module. The difference between temperature in the center and bottom of the PV module is measured. In the center of the PV module temperature is 53.1°C while at the bottom it is 49.6°C. The frame supporting the FPV modules also has the same temperature of 45.5°C, and water has a comparatively less temperature of 33.3°C.

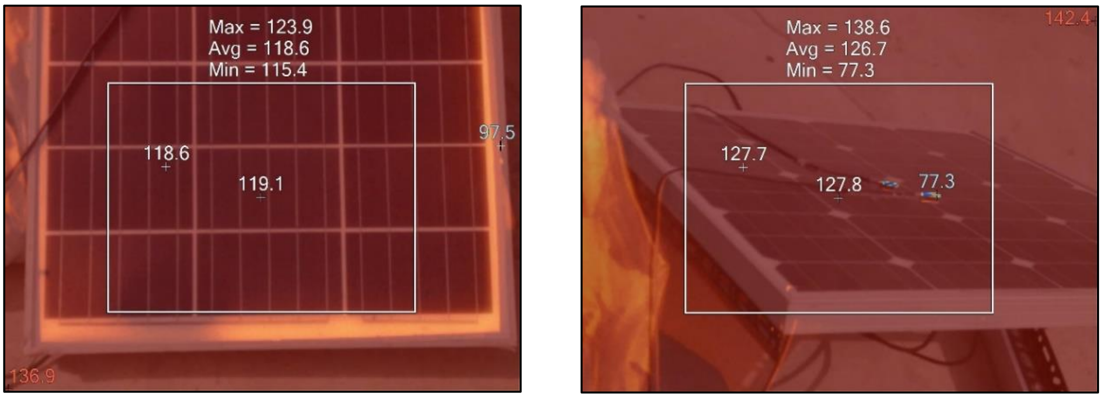


4.28 (A) 4.28 (B)

4.28 (C) 4.28 (D)

Figure 4.28: Thermal Imaging of FPV Modules - 15 Degree Experiment 4.28(A) Thermal Imaging of Mid of FPV Module, 4.28(B) Thermal Imagining of Bottom of FPV Module, 4.28(C) Thermal Imaging of Frame of FPV Module, 4.28(D) Thermal Imagining of Water in Pond Simulator

Similarly, thermal imagining of OPV modules has been done to study their thermal behavior as shown in Figure 4.29. Figure 4.29 (A and B) represent that the OPV module has a center temperature of 53.2°C while the temperature at bottom of the module is 48.3°C and the roof temperature is about 61.1°C. The front side of FPV and OPV modules have a thermal difference of 0.1 °C. Around 4-6°C, the back temperature difference has been seen in Figure 4.27, this is due to the base temperature of the FPV and OPV system. In the FPV system base, water temperature and OPV system base roof have a temperature difference of 27.8°C, hence causing back temperature difference in the systems.



4.29 (A)

4.29 (B)

Figure 4.29: Thermal Imaging of OPV Modules - 30 Degree Experiment 4.29 (A) Thermal Imagining of Bottom of OPV Module, 4.29 (B) Thermal Imagining of Center of OPV Module and Roof

4.4.4 Power Conversion

The voltage and current of each panel are measured by connecting voltage and current sensors in the circuit. It is observed that there is more deviation in voltage as compared to the current due to a change in PV panel temperature. Maximum values of power produced are observed in between 12-1 Pm. During day 1 FPV mono produced 85W, FPV poly produced 81.4W, OPV mono produced 69.9W and OPV poly produced 66W respectively. During day 2 and day 3 in between 12-1 pm, FPV mono produced 88.8W and 82.5W, FPV poly produced 85.2W and 79.2W, OPV mono produced 71.4W and 68.3W while OPV poly produced 67.4W and 65.7W. From Figure 4.30, it can be noted that trends of power produced by FPV mono module are highest followed by FPV poly module, OPV mono module, and OPV poly module respectively. The greater efficiency of the FPV system is because the water body provided the cooling effect and the ambient temperature and relative humidity above the FPV system is less as compared to the OPV system as shown in Figure 4.25,Figure *4.26*. While FPV module temperature decrease due to cooling effect, OPV module temperature increase due to increased temperature of the rooftop as shown in Figure 4.27 and Figure 4.29(B).

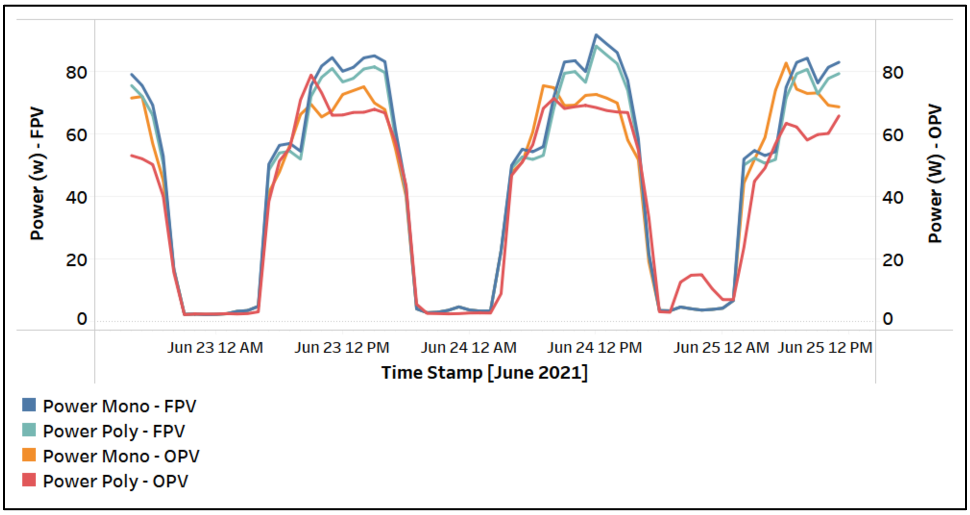


Figure 4.30: Trends of Power Production from FPV and OPV system - 15 Degree

4.5 Thermal Comparison between Different Tilt angles

FPV and OPV systems were analyzed at different tilt angles as discussed above. Metrological conditions were almost the same with a solar radiation difference of 57 W/m^2 between all three experiments while there was a 2-4°C ambient temperature difference. Water temperature variation was between 33-38°C. From the trends obtain and the results of thermal imaging it is observed that the maximum temperature difference between the front of FPV and OPV module at 0-degree tilt angle was 2-4°C, similarly, at 15-degree tilt and 30-degree tilt angle maximum temperature difference was 1 °C and 3-3.5°C. The maximum module back temperature difference observed between FPV and OPV modules at 0-degree tilt angle was 10-11°C, while at 15 and 30-degree tilt angle maximum module back temperature difference observed was 7-9°C and 4-6°C. It is also observed through thermal imaging that OPV module front temperature is almost linear at all 3 tilt angles. FPV modules at 0-degree tilt angle have linear front temperature having only a difference of 0.5°C. While at a 15-degree tilt angle there is a temperature gradient of 1.1 °C between module middle and bottom part and at 30-degree tilt angle, 3.5°C temperature gradient is observed between the middle and bottom of the module. As the bottom part is near to the base surface hence in the case of 15 and 30-degree tilt angle FPV bottom part receives more cooling as compared to the middle part. Hence, we can conclude that at 0-degree tilt angle modules receives a uniform cooling effect from the water due to which there is a maximum back temperature difference of 10-11°C between FPV and OPV modules. But as we increase the tilt angle to 15 and 30-degree, the middle part receives less cooling effect due to which the back temperature difference between FPV and OPV modules reduce to 7-9°C and 4-6°C.

4.6 Power and Optimal Tilt angle

Overall power produced in 3 days by individual PV modules at different tilt angles is shown in Figure 4.31. The power produced by the modules placed at a 30-degree tilt angle (optimal angle for Islamabad) performed better as compared to 15 and 0-degree tilt angles. However, if we compare the performance of FPV modules placed at 0, 15, and 30-degree tilt it can be noted that modules at 0-degree outperformed modules at 15-degree tilt. But in the case of OPV modules, it is the opposite, modules at 15-degree tilt outperformed modules at a 0-degree tilt. Despite modules placed at 0 and 15-degree tilt gets more benefit from cooling effect as being close to water, yet energy produced by them is lower as compared to modules placed at 30-degree tilt. At a 30-degree tilt, the FPV mono module produced 9.07% more energy in 3 days as compared to OPV mono modules while FPV poly produced 9.7% more energy in 3 days as compared to the OPV poly module. Similarly, if we compare the FPV mono module with the FPV poly module at a 30-degree tilt, FPV mono produced 4.17% more energy. And OPV mono produced 4.98% energy as compared to OPV poly module. This can be clarified by the fact that optimizing PV module tilt angle is more definite than cooling effect. In a conclusion, it is recommended to adjust the optimal tilt angle for both OPV and FPV systems. Also, monocrystalline PV modules perform better in both systems.

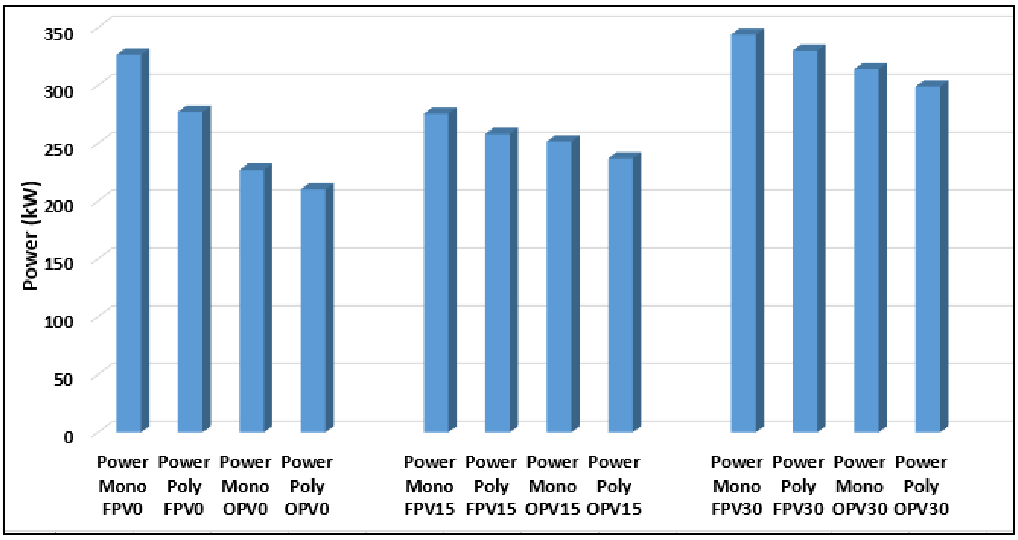


Figure 4.31: Power Comparison at Different Tilt Angles

Summary

The testbench includes monocrystalline and polycrystalline PV modules for evaluating their performance on a water body. It contrasts the advantages of the FPV system and the OPV system. Several experiments have been carried out to investigate the effect of metrological parameters on the thermal and electrical behavior of FPV and OPV systems operating under Pakistan climate conditions. Moreover, the test bench includes a fully automated measuring station to measure all the parameters required for analysis which has never been proposed for the FPV test bench. The following are the key findings of the study: FPV systems reduce water evaporation by around 17 percent when partially covered and by around 28 percent when fully covered, saving water. The average temperature of both monocrystalline and polycrystalline FPV modules is 2-4°C lower at the angles tested during the period. Similarly, the back of FPV modules is cooler than the back of OPV modules, with a 5-11 °C difference on average. The results show that the water body provides an adequate cooling effect to improve the FPV module's performance, whereas the OPV module's performance degrades due to heat gain from the roof. Thermal imaging and PV module temperature trends revealed that the cooling effect benefits the FPV module at 0 degrees tilt more than the FPV module at 30 degrees tilt. Around 4°C front temperature deviation has been observed due to the tilt angle. Through thermal imagining, it is also observed that at 0-degree tilt, PV modules have a uniform front temperature. By increasing the tilt, the bottom part gets to benefit from the cooling effect of water; around 1.1°C temperature gradient was observed at 15-degree tilt, and a 3.5°C temperature gradient was observed at 30 degrees. FPV modules produce an average of 3% more energy in a day as compared to OPV modules under prevailing metrological conditions. Adjusting optimal tilt angle for both FPV and OPV systems is recommended. Although the cooling effect decreased at 30-degree tilt, unlike 0-degree tilt, 30-degree modules produced 10-17% more energy. Stating these results and results discussed in the literature, FPV systems provide a promising growth as they reduce the cost of PV installation in terms of space, provide better efficiency as compared to OPV systems. Also helps in saving water by reducing evaporation. This technology can benefit Pakistan as there are many water resources and dams with which FPV can integrate, saving a huge cost of the transmission system.

Chapter 5: Conclusions and Recommendations

5.1 Conclusions

A simple testbench has been developed for demonstration and research purposes on the FPV system. The testbench incorporates mono and polycrystalline PV modules to study their performance on a water body. It compares the benefits of the FPV system as compared to the OPV system. Several experiments have been done to investigate the impact of metrological parameters on the thermal and electrical behavior of FPV and OPV systems, operating under Pakistan climatic conditions. Keys results of the research carried out are:

- FPV systems reduce water evaporation by around 17 percent when partially covered and by around 28 percent when fully covered, saving water.
- During the period, the average temperature of both mono and polycrystalline FPV modules is 2-4°C lower at the angles tested. Similarly, the back of FPV modules is lower than OPV modules with an average difference of 5-11°C. Results show that the water body provides an adequate cooling effect to increase the performance of the FPV module while the OPV module's performance degrades due to heat gain from the roof.
- Thermal imaging and PV module temperature trends showed that at 0-degree tilt FPV module gets more benefit from the cooling effect as compared to the FPV module at 30-degree tilt. Around 4°C front temperature deviation has been observed due to the tilt angle.
- Through thermal imagining, it is also observed that at 0-degree tilt PV modules have a uniform front temperature. By increasing the tilt, bottom part gets to benefit from the cooling effect of water, around 1.1°C temperature gradient was observed at 15-degree tilt and a 3.5°C temperature gradient was observed at 30 degrees.
- FPV modules produce an average of 3% more energy in a day as compared to OPV modules under prevailing metrological conditions.
- Adjusting optimal tilt angle for both FPV and OPV systems is recommended. Although the cooling effect decrease at 30-degree tilt unlike 0-degree tilt 30-degree modules produced 10-17% more energy.

Stating these results and results discussed in the literature, FPV systems provide a promising growth as they reduce the cost of PV installation in terms of space, provide better efficiency as compared to OPV systems. Also helps in saving water by reducing evaporation. This technology can benefit Pakistan as there are many water resources and dams with which FPV can integrate, saving a huge cost of the transmission system.

5.2 Future Recommendations

- Based on experiments carried out and drawbacks faced, the next stage of research should focus on.
- Improved measuring station which transfers data online to a database so that experiments can be carried for a whole year which will make data analysis easy and accurate.
- Waterproof sensors should be integrated with the measuring station to perform tests in any weather condition.
- Gathering data set for a whole year for forecasting and fault detection in FPV system as compared to OPV system.

Acknowledgment

I want to thank Allah Almighty, The Most Beneficent, The Most Merciful Who made me able to complete the research thesis. I express my sincere gratitude to Dr. Adeel Waqas for being such a tremendous mentor and guiding me throughout this outstanding journey. His illuminating views, constructive criticism, and consistent feedback made me sail through numerous obstacles that came in the way. I also extend my humble gratitude to all the faculty and GEC members especially Sir Abdul Kashif Janjua for his unconditional support. I pay special regards to my sister, brother, and friends for their constant encouragement and prayers that have made this endeavor easy and tireless. In the last but not least, I pay special tribute to my parents who has always been my biggest supporter.

Appendix 1 - Publications

Thermal and Electrical Performance of Solar Floating PV System Compared to On-ground PV System-An Experimental Investigation. Hamza Nisar[1], +Abdul Kashif Janjua[1,2], Hamza Hafeez[1], Sehar Shakir[1], Nadia Shahzad[1], Adeel Waqas[1]*

Abstract

Floating Photo Voltaic (FPV) is a relatively new concept for producing clean green energy. FPV offers an alternative to the high cost of land for On-Ground PV (OPV) systems while mitigating the environmental effects caused by OPV systems. This study presents the results of an experimental investigation of a small-scale FPV system. The goal is to evaluate and compare the thermal and electrical performances of mono and polycrystalline PV modules used in FPV with those of an OPV system with a similar nominal capacity. To accomplish this, a test bench consisting of an FPV and an OPV system, as well as a measurement station, has been proposed and established. This paper elaborates on the experimental setup of the complete test bench. The results show that when the water body is partially covered with an FPV system, water evaporation is reduced by 17%, and it is reduced by around 28% when fully covered. It was also found that water bodies provide an adequate cooling effect, lowering the front temperature of FPV modules by 2-4% and the back temperature by 5-11% compared to OPV modules. Thermal imaging revealed that at 0 degrees of tilt, the front temperatures of the modules are uniform. Still, as the tilt increases, a temperature gradient is observed between the bottom and middle parts of the modules. In addition, an experimental test was performed to compare the power generation of FPV at varying tilt angles. The test results show that the FPV system produces the most energy when installed at the annual optimal tilt angle. As a result, for FPV, adjusting the Photovoltaic panels to their optimized tilt angle is also recommended.

Key Words: PV system, Floating Photovoltaic System (FPV), Floating PV testbench, Evaporation, Thermal imagining, Thermal behavior, Energy efficiency, Cooling effect, Pakistan

Journal: Renewable Energy

Impact Factor: 8.01

Status: Under Revision