Performance assessment of Trombe wall and south façade as applications of building integrated photovoltaic systems

By

Muhammad Siddique

Reg. No.: 00000327146

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Supervised by

Dr. Nadia Shahzad

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National University of Sciences and Technology (NUST)
H-12, Islamabad 44000, Pakistan
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Signature: ________________________________

Name of Supervisor: Dr. Nadia Shahzad

Date: __________________________

Signature (HOD): __________________________

Date: ______________________________________

Signature (Dean/Principal): ___________________

Date: ______________________________________

Certificate

This is to certify that work in this thesis has been carried out by **Mr. Muhammad Siddique** and completed under my supervision in Solar Energy lab, USPCAS-E, National University of Sciences and Technology, H-12, Islamabad, Pakistan.

Supervisor: ______________
Dr. Nadia Shahzad
U.S.-Pakistan Center for Advanced Studies in Energy
NUST, Islamabad

GEC member 1: ______________
Prof. Dr. Adeel Waqas
U.S.-Pakistan Center for Advanced Studies in Energy
NUST, Islamabad

GEC member 2: ______________
Dr. Sehar Shakir
U.S.-Pakistan Center for Advanced Studies in Energy
NUST, Islamabad

GEC member 3: ______________
Abdul Kashif Janjua
U.S.-Pakistan Center for Advanced Studies in Energy
NUST, Islamabad

HOD-ESE: ______________
Dr. Rabia Liaquat
U.S.-Pakistan Center for Advanced Studies in Energy
NUST, Islamabad

Principal: ______________
Prof. Dr. Adeel Waqas
U.S.-Pakistan Center for Advanced Studies in Energy
NUST, Islamabad

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Abstract

Building integrated photovoltaics (BIPV) technology can lead the world to establish sustainable buildings. Technically, this technology is struggling with low electrical power generation due to building structural limitations and elevated temperature, also performance of BIPV systems analyzed only based on their electrical output. Moreover, BIPV application as Trombe wall system significantly reduce the output power due to presence of glass in front of module. Thus, this paper presents an experimental study of two distinct BIPV wall systems and analyzed them based on their electrical, thermal and combine performance. Maximum electrical efficiency of BIPV south façade (BIPVSF) and BIPV Trombe wall (BIPVTW) was 6.02% and 3.96% respectively. The BIPVSF had a daily average thermal efficiency of 11%, whereas the BIPVTW achieved an efficiency of 38.52%. Furthermore, BIPVSF and BIPVTW systems respectively achieved daily average combine (electrical and thermal) efficiencies of 13.16% and 39.67%. The daily electrical power of BIPVSF system was 38.6% more than that of the BIPVTW but daily heat gain of BIPVTW system was 3.2 times of BIPVSF system. Despite the fact that the electrical power output is diminished when photovoltaics is used as BIPVSF and BIPVTW, the hybrid use of both systems can furnish a decent combined efficiency.

Keywords:

Solar photovoltaics, Sustainable Buildings, Building integrated photovoltaics, BIPV, Solar Façade, BIPVTW, PV/T.

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Experimental study on the performance of BIPV south façade and BIPV Trombe wall system.

Muhammad Siddique [a], Nadia Shahzad [a], Shayan Umar [a], Adeel Waqas [a], Sehar Shakir [a], Abdul Kashif Janjua [b, c]

[a] U.S-Pakistan Center for Advanced Studies in Energy (USPCAS-E), National University of Sciences & Technology (NUST), H-12 Campus, Islamabad, Pakistan

List of Abbreviations

PV	Photovoltaic
mono-PV	Monocrystalline PV module
poly-PV	Polycrystalline PV module QASP
GHG	Greenhouse gasses
Voc	Open circuit voltage
Isc	Short circuit current
Imax	Maximum current
Vmax	Maximum voltage
BIPV	Building Integrated Photovoltaics
TW	Trombe Wall
BIPVTW	Building Integrated Photovoltaics Trombe Wall
BIPVSF	Building Integrated Photovoltaics South Façade
GHI	Global Horizontal Irradiance
DNI	Direct Normal Irradiance
G	Irradiance
A	Area
m	mass
Cp	Specific Heat Capacity
T	Temperature
V	Volume
Q	Heat Gain

Chapter 1

Introduction

Due to rapid population expansion and improvements in people's living standards, it is anticipated that the demand for energy on a global scale will increase anywhere from 1.5 to 3 times higher by the year 2050.(1). The consistent demand for energy around the world is primarily met by burning fossil fuels, which is the primary factor in the production of greenhouse gases (GHGs) on a worldwide scale (2). It takes millions and millions of years for fossil fuels to replenish themselves, hence they are not considered a renewable power source. Both the increasing scarcity of fossil fuels and the negative impact they have on the environment are driving the global transition to more sustainable forms of energy (3,4). It may be time-consuming and expensive to develop new sources of renewable energy to meet the necessary demand for energy, but it is possible to minimize energy demand through energy conservation efforts. These days, the most important problems involve cutting down on total energy demand as well as consumption of fossil fuels (5).

In order to maintain comfortable indoor conditions, the building industry consumes over 40% of the world's total energy supply (6). The International Energy Agency has released a paper in which it states that if energy saving technologies are not implemented in the building sector by the year 2050, then the amount of energy that is consumed might grow by as much as fifty percent (5). Thus, with contribute to energy efficiency improvements, zero-energy buildings can be established by the deployment of renewable energy technology onto the structure to meet the sector's energy need on-site and reduce carbon emissions by lowering the total energy demand of the world (7). Production and consumption of power on site can also help cut down on the expensive costs of constructing and maintaining transmission infrastructure, as well as the losses those systems incur (8,9). In this way the world’s dependency on fossil fuels and their environmental impacts can be curtailed.

The use of solar photovoltaics, in comparison to other forms of renewable energy, is particularly well-suited for the onsite production of electricity within buildings. In the case of a building application, there are two techniques to install solar photovoltaics: building applied photovoltaics (BAPV) and building integrated photovoltaics (BIPV). BAPV is the process in which we apply photovoltaic modules onto the building with the help of various structures, but BIPV is the technique in which the conventional building material is replaced with the photovoltaic material, and it became a part of the building envelop. BAPV stands for building-applied photovoltaics, and BIPV stands for building-integrated photovoltaics. As a result of the fact that the BIPV system is an empirical, unique, and promising application to achieve net-zero energy and net-zero emission buildings, there is a great market potential for the BIPVT system all over the world (10). The integration of photovoltaic technologies into the building structure not only eliminates the need for additional space for the installation of photovoltaic systems but also helps to cut down on the additional costs of the structure and generates energy within the building while taking into account environmental impact of building and its aesthetic value (11,12). In China, for instance, there are special supports or benefits available for BIPV, such as the RMB 20 for each watt subsidy program for BIPV initiatives that started in March 2009. That's just one way the government of some countries is trying to get individuals to go over to this method of doing things (12). With all these advantages, building integrated photovoltaics (BIPV) are quickly becoming more popular in the photovoltaic industry. There are a number of research scholars who have attempted to compile the information about BIPV systems by writing review articles (13–17). Additionally, there are a number of articles that have been published on research and development of BIPV wall systems (18–20), BIPV roofs systems (21–24) and BIPV cladding systems (25–27).

Simulations formed the basis for a significant percentage of the work in these research studies. Therefore, it is still necessary to test these technologies experimentally in real-time scenarios. Furthermore, in most of the cases we classify BIPV system just based on its electrical or thermal performance, but we need to examine it based on its combined (electrical and thermal) performance. When BIPV systems are installed as Trombe walls, the thermal comfort of the building is improved; however, this comes at the expense of the electrical power of the Photovoltaic module. Therefore, further research into these systems is still required to fully understand them.

1.1 Problem Statement

Meeting the requirements of an ever-increasing energy demand is an enormous obstacle that the entire world is currently confronted with. After that, transmitting energy to the facilities requires a significant amount of funds, and it also results in the waste of a significant amount of energy due to transmission losses. In spite of the vast opportunities presented by BIPV applications, a number of challenges must first be overcome in order to see widespread use of the technology. These include technological, social, and economic concerns. (28,29).

While designing BIPV walls, there are limitations that can be faced. Generally, in case of BIPV walls it is mandatory in most of the cases to install PV modules at 90° tilt angle and it cost us to compromise the output power of the PV module. Furthermore, limitations regarding azimuth angles are also there as all walls of a building do not receive equal number of solar radiations.

In addition, when sun rays hit a PV module, some part of this energy is transformed into the creation of electrical power, while remaining energy is transferred into heat When it comes to solar facades that have integrated PVs modules, the temperature of modules rises more than the ones that are mounted in open air, which ultimately decrease the amount of electrical power that they produce (30). In the case of solar photovoltaics, the temperature and the amount of power generated have a close relationship with one another. Temperature increases might reduce the amount of electrical power produced. The most significant challenges that building-integrated photovoltaics, or BIPV technologies are currently facing include an increase in the temperature of PV modules as well as limitations concerning tilt angle and azimuth angle.

1.2 Objectives of study

The fundamental and overarching goal of this thesis is to conserve energy by lessening the amount of heating load in buildings and making use of building-integrated photovoltaic systems (BIPV) to satisfy the necessary amount of heating load in those structures. After that, creating clean and green energy inside the premises to lessen the losses of transmission and evaluating BIPV systems not only by the amount of power produced but also based on its performance in terms of both electrical and thermal output. These are the goals of the study.

- To create a BIPV wall system that can be configured in two distinct ways.
- To Investigate the BIPVSF and BIPVTW systems according to the electrical performance of each.
- To investigate both BIPV south façade system and BIPV Trombe wall system based on their thermal performance.

- To examine recommended systems based on combine of (electrical and thermal) performance.

1.3 Scope of Study

Different configurations of solar modules installed as part of a building integrated wall system were tested to determine their electrical performance in this study. It was also looked into how much these modules could raise the average temperature of the air inside by analyzing their thermal performance. Afterwards, the proposed systems were assessed according to how well they functioned as a whole (both electrically and thermally). The solutions that have been recommended can be employed as part of a hybrid system to create clean and green electrical energy on the premises of the business. Additionally, energy can be saved by reducing the amount of heating load that is required.

1.4 Limitations of Research

Because we had few resources available, we were only able to conduct a limited version of this study. In addition, Pakistan did not have any of the most recent technological advancements and importing them from other countries was a time-consuming and expensive process. Therefore, only the polycrystalline silicon technology was considered for this analysis.

1.5 Thesis Structure

The organizational structure of the thesis is depicted in Figure 1-1.

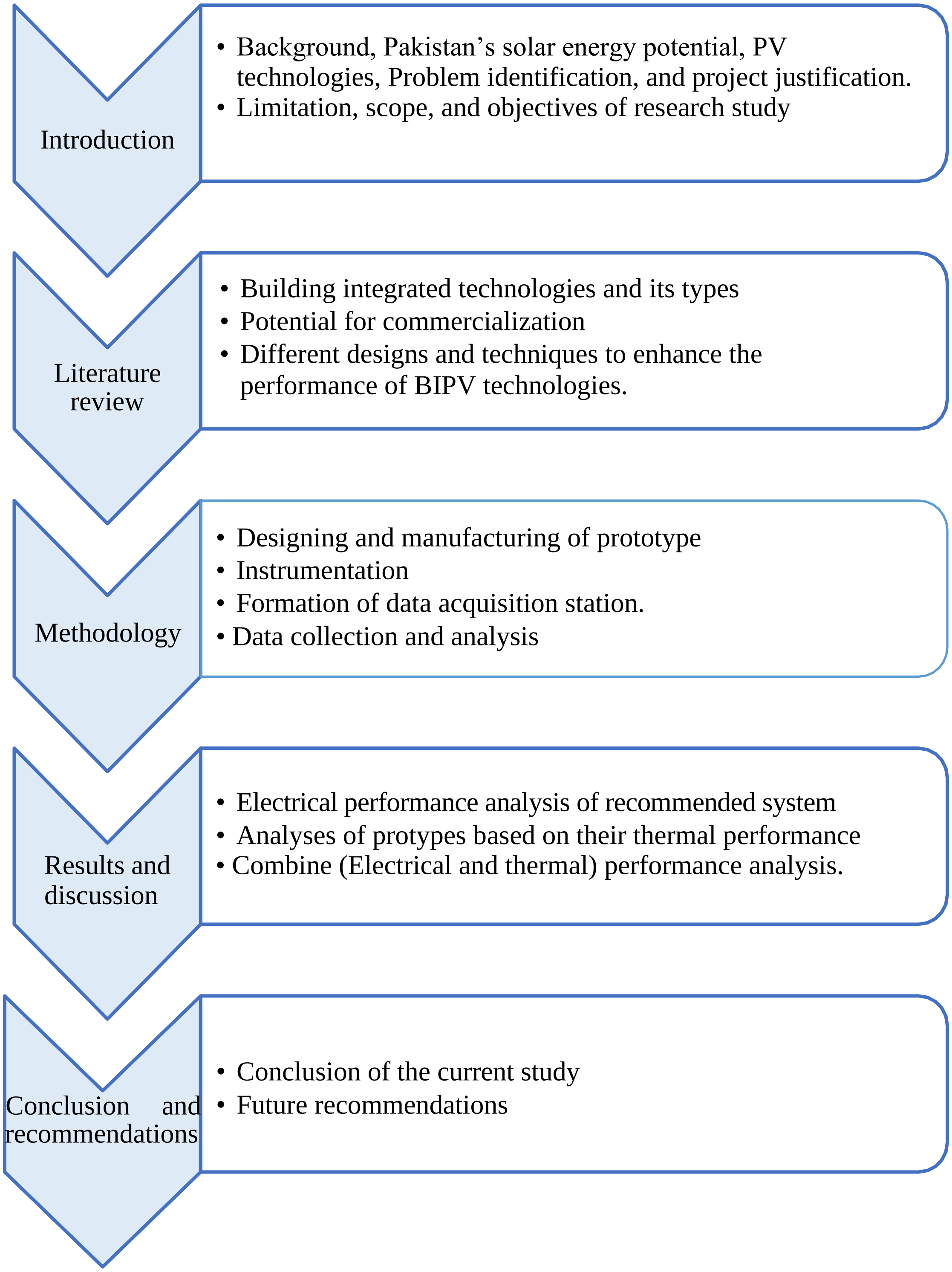

Figure 1-1. Structure of Thesis.

Summary

This chapter discussed an explanation of significance of solar energy as well as Pakistan's potential to benefit from it. The topic at hand is building integrated photovoltaic technology as well as its various forms. In the case of BIPV technologies, there are several issues that have been brought to light, including structural limitations and poor electrical performance as a result of high temperatures experienced by PV modules. The key goal of this research is to find ways enhance energy performance by decreasing the amount of heat required to maintain a given temperature and to optimize the overall hybrid performance of the BIPV systems in terms of both their electrical and thermal capabilities. In addition to a literal analysis of the thesis's framework, the conclusion also addresses the study's scope and any constraints that should be considered.

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Chapter 2

Literature Review

2.1 Solar Energy

Radiation from the sun is a potent energy source that can be converted into heat, be the catalyst for chemical reactions, or be used to generate electricity. Solar energy can do all three of these things. Solar power might turn out to be the most viable option for the world of the future for many reasons: Energy coming from sun is the most widespread source of greener energy, and it comes at a rate of 3.8×10^{23} kW, from which nearly 1.8×10^{14} kW is captured by the earth. First, energy from solar is one of the abundant energy source (1). Energy from Sun can be received on earth in a variety of forms, including light and heat. Most of this energy is dissipated during its journey as a result of cloud scattering, cloud reflection, and cloud absorption. According to recent research, the world's need for energy can be easily and effectively met by harnessing the sun's free and abundant solar power, which is also a source of energy that does not incur any financial costs (2). Second, it has great potential as a global energy source because it can never be burned up (3). The efficiency of the solar PV sector is heavily dependent on the distribution and intensity of solar radiation. There is considerable variation in these two factors between countries. Figure 2-1 presents the map of global horizontal irradiance.

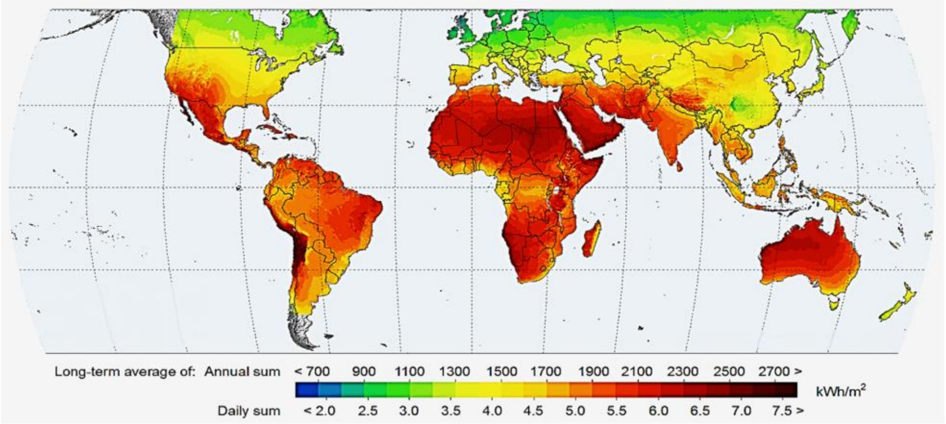


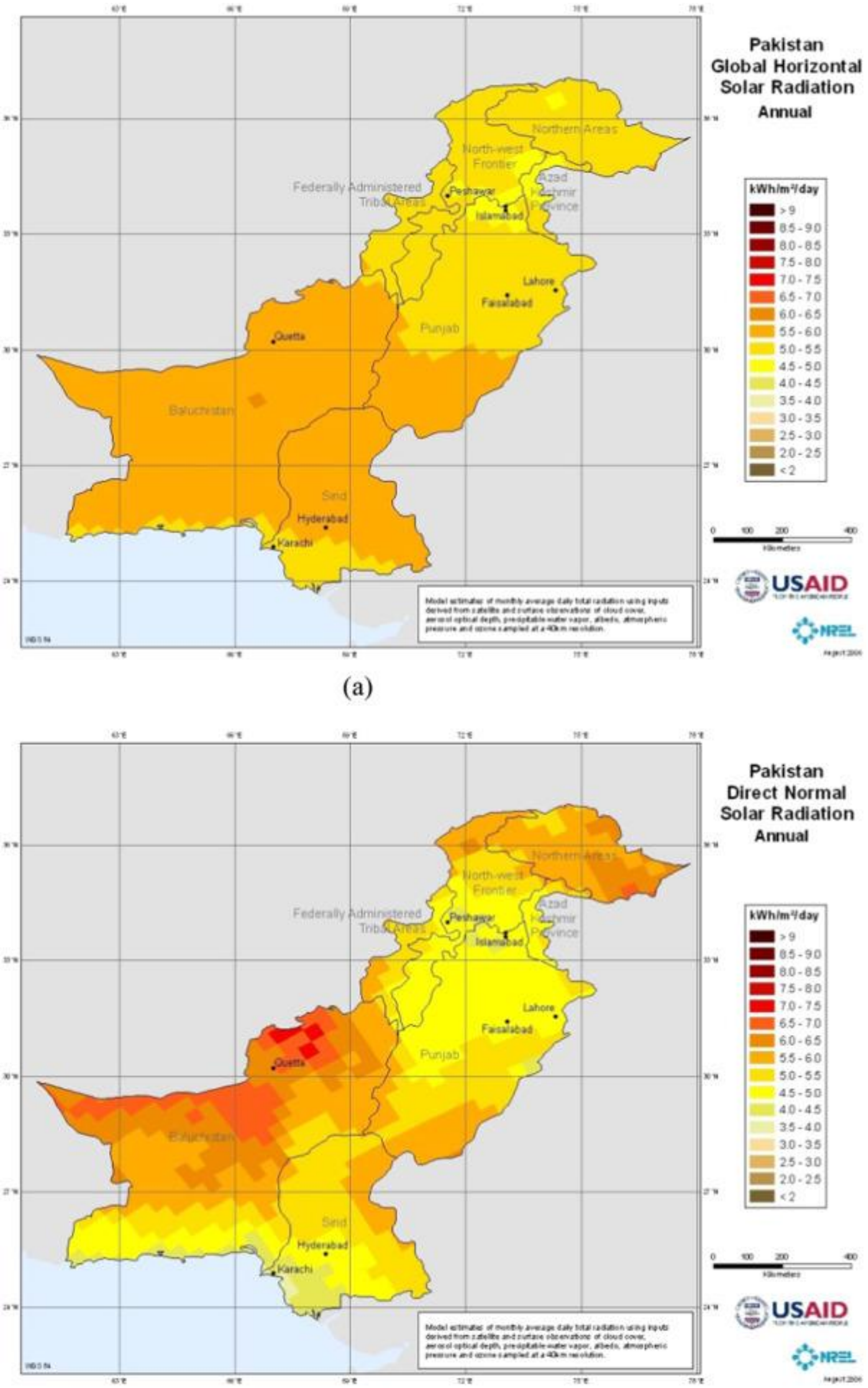
Figure 2-1. Maps of Global Horizontal Irradiance (GHI) (1).

In comparison with other countries, those in Asia have the greatest potential to receive solar radiation because the sun shines for a longer period throughout the year in those countries. It is essential to keep in mind that a major part of the radiations from sun is not utilized and is, in effect, lost (4). Solar radiation is present in large enough quantities in many countries, particularly developing countries, for its beneficial utility to be utilized (5). The amount of solar radiation that reaches a specific area does, however, vary depending on that site's latitude and longitude, the amount of solar radiation that is available throughout the country is sufficient to support the growth and use of a wide range of solar energy systems. (6). Several elements, including source availability, local technology, cost, public awareness, government policies, and a willingness to invest in alternative energy technologies, are critical for the development and implementation of solar energy applications on a national level.

2.2 Potential of Solar Energy in Pakistan

Energy from the Sun can be harvested and utilized effectively on a national scale in Pakistan because of the country's favorable geographic location, topography, and climate. Annually, the country receives somewhere in the range of 1900-2200 kWh/m^2. As a result, Pakistan possesses a significant amount of potential solar energy resources. Due to the fact that the country has a consistent distribution of solar radiation, it is extremely beneficial and suitable for the deployment of solar-based applications. This is because the country is ideally suited for the deployment of such applications (7). According to the findings of several studies, approximately half of the country is best suited for the location of bigger solar power plants applications and utilities because it receives a greater amount of solar radiation (8). The Baluchistan province receives approximately 20 MJ/m^2 of daily global insolation, making it one of the provinces with the highest solar energy potential. These circumstances are ideal for several applications of solar energy, including solar photovoltaics (PV) and solar thermal energy. Figure 2-2 displays a solar resource map of Pakistan with a high resolution for one year's worth of data (7).

There is a wide range of cutting-edge technology that can be utilized to harvest this massive amount of energy. Solar photovoltaics and solar thermal are the two primary solar technologies. Solar thermal technologies are used to convert solar radiations into thermal energy, while solar photovoltaics are used to convert solar radiations into electricity.



(a)

(b)

Figure 2-2. Annual daily mean solar irradiance (kWh/m^2) with the help of NREL's CSR model (7) (a) GHI (b) DNI

2.3 Solar Photovoltaic Devices

Solar PV modules, made up of photovoltaic (PV) cells, are the device that is used to transform energy from sun into usable electrical power. Solar photovoltaic modules are made up of series-parallel combination of small cells and these photovoltaic cells are manufacture by the combination of P-type and N-type semiconductor materials during manufacturing process (9). The upper side of solar photovoltaic module is exposed to sunlight, which causes the material to absorb photons from the sun and produce flow electrons, which are then collected by an external circuit. Crystalline solar photovoltaics modules are the only type of photovoltaics devices that are both commercially available and have reached a mature stage of development. Although various kinds of solar PV technologies have been developed and manufactured up until now, three generations of solar PV module technologies have been produced (9). The solar photovoltaic technologies that are currently available on the market can be broken down into the following categories:

2.3.1 Monocrystalline Solar PV Modules

Crystalline solar cells with monocrystalline structures are the most advanced and efficient type of solar panel technology, producing an output of approximately 22 percent of their rated power. These cells belong to the class of crystalline solar cells. At temperatures between 30 and 35 degrees, monocrystalline photovoltaics, also known as mono-PV, perform best. As a result of the round shape of the ingots that are used in the manufacturing of monocrystalline solar cells, a cut is made on the edge of each cell and these cells are dark in appearance. Solar PV modules made of monocrystalline solar PV cells are more efficient than those made of polycrystalline. In addition to this, monocrystalline technology is considered to be of the first generation photovoltaic cells (10).

2.3.2 Polycrystalline Solar PV Modules

Polycrystalline solar cells come from the same family as monocrystalline cells, but their structure of atoms is different. In monocrystalline technology, the sequence of the crystalline structure is defined, clear and uniform, but in polycrystalline technology, the sequence of structure is not uniform. These kinds of photovoltaic modules are also referred to as first-generation solar cells. Because they have a lower temperature coefficient, poly-crystalline photovoltaics cells can operate well at lower temperatures as compared to those of monocrystalline solar cells. The efficiency of solar modules made with polycrystalline solar cells technology is marginally lower than that of modules made with monocrystalline silicon technology. A polycrystalline silicon solar photovoltaics cell typically has a square shape and a bluish hue.(11)

2.3.3 Amorphous Silicon Solar PV Modules

Thin-film solar cells from the second generation are used to construct amorphous silicon modules. The solar cells of today are second-generation technology. Although the cost of thin-film solar cells is far cheaper than that of crystalline solar cells, the technology is still in its early phases of development and has a lower efficiency. It is also applicable to the utilisation of flexible materials. Amorphous silicon is finding an increasing variety of uses. (12)

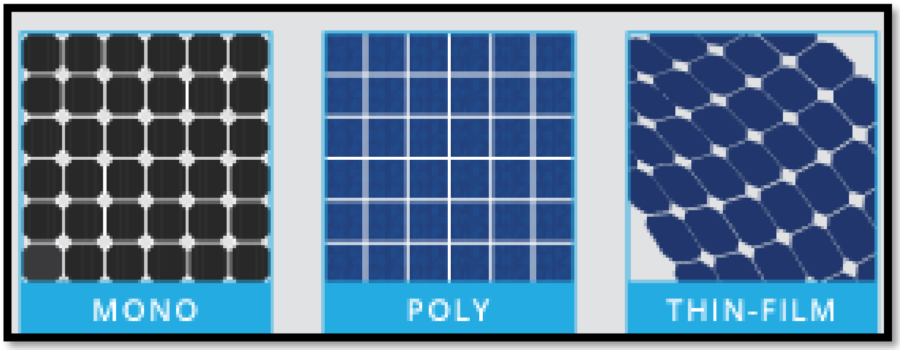


Figure 2-3. Visuals of different technologies of Solar cells.

2.3.4 CIGS Solar PV Modules

Another member of the second generation of solar cells is CIGS (cadmium indium gallium selenide) solar PV technology. To achieve a higher level of solar cell efficiency, it is constructed out of a variety of materials that are combined. This variety of solar cell makes use of the elements copper, indium, gallium, and selenium as its constituent parts. On the other hand, they can be produced using substrate materials that are inexpensive and at low temperatures. The thin-film solar cell has an efficiency of 21%. The use of multiple types of material can both cut costs and boost productivity without sacrificing quality. (13)

2.3.5 Cadmium Telluride Solar PV Modules

The cadmium telluride solar cell is a member of the family of solar cells that belong to the second generation. It has the highest efficiency of the single-junction solar cells, which is 26%. In addition to its widespread use in commercial projects, it is one of the PV solar cells with the highest usage rate. Materials such as cadmium and telluride are utilised during the manufacturing process of solar panels. Cadmium telluride solar cells are the most popular type of second-generation solar cells used in commercial applications.(14)

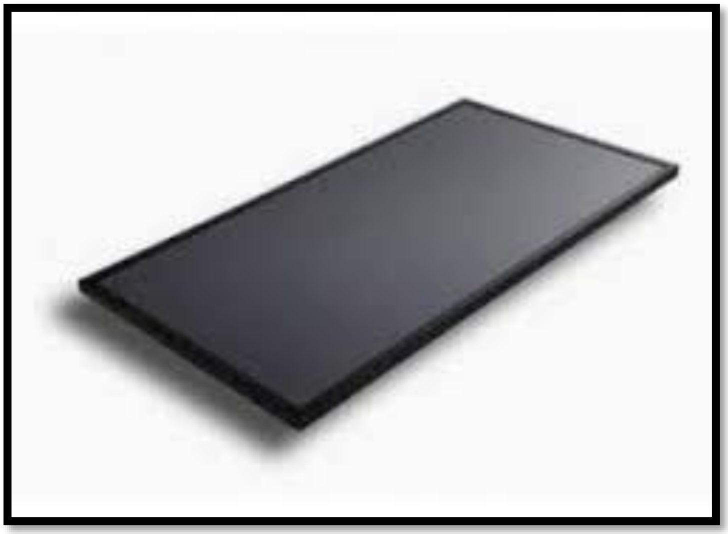


Figure 2-4. CIGS Solar Panels

2.3.6 Multi Junction Solar PV Modules

The multi-junction solar cell has the highest efficiency of any PV solar cell, which is close to about 54%. In this type of solar cell, multiple types of solar cells are stacked together to effectively harvest solar energy. Each type of material can absorb a particular wavelength of the electromagnetic wave from solar radiation. This technology is still in the process of being developed, and the cost of the solar cell is significantly higher than the cost of a crystalline solar cell. The multi-junction approach is based on the quantum tunnelling principle, according to which the wave property of photons is exploited in order for them to traverse the potential barrier.(15)

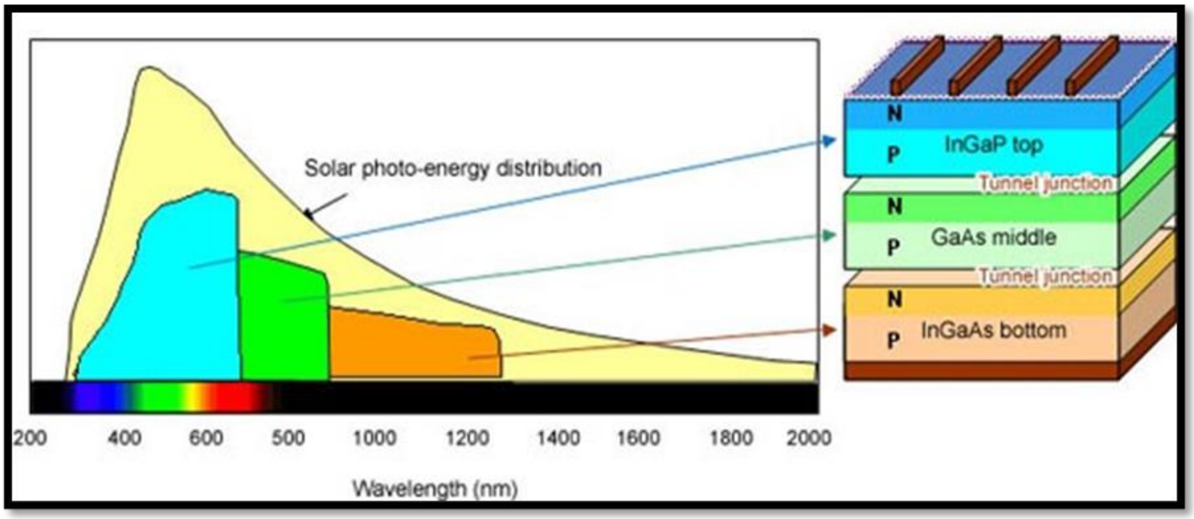


Figure 2-5. Multi Junction Solar Cells

2.3.7 Advanced Solar PV Modules

Advanced solar PV modules are made up of organic or perovskite cells and this technology of modules belong to the third generation of solar cells; however, there is currently no organic solar cell technology available commercially. Up to this point, the efficiency of the Perovskite solar cell has been measured at 13%; however, the lifetime of solar cells is very short and averages around 10 years. However, the price of a solar cell made of perovskite is significantly lower than that of a solar cell made of crystalline material. [8]

2.4 IV CHARACTERISTICS OF PV SOLAR MODULES

The technology known as solar photovoltaics works by converting the solar energy into electricity. Semiconductor material (P and N type) is what makes up solar photovoltaic, and it is this material that captures the photon and generates the flow of electrons (current). Through analysis of the IV characteristics, one can determine the power generated by solar photovoltaics. IV characteristic curves of solar cells are a graphical representation of the relationship between the current and voltage of the cell when subjected to particular combination of irradiance and temperature. The IV characteristic curve is utilized in the process of optimizing the solar cell performance to achieve the maximum possible PowerPoint. Graph shown in the figure below represents a typical example of an IV curve for PV solar power when operating under standard conditions.(16). The product of a PV solar cell's current (I) and voltage (V) is the cell's output power (P). A graph of the current and voltage (IV) characteristic curve can be obtained by performing multiplication on voltage and current readings point by point. Open circuit voltage is measured in a solar cell when there is no load connected to it while the current is zero (Voc) (17). However, short circuit current is calculated by connecting positive terminal of solar cell with the negative terminal of solar cell in series, causing the voltage across the solar cell to drop to zero, a phenomenon known as short circuit current occurs in the solar cell. This causes the current in the solar cell to reach its maximum value (ISC). A solar cell's IV characteristics have the potential to have the greatest possible range between the short circuit current and open circuit voltage. In actual practice, neither of these two points produces any power; however, they are regarded as the lower and upper limits of the IV characteristics, and the maximum point must be situated somewhere in between them (18).

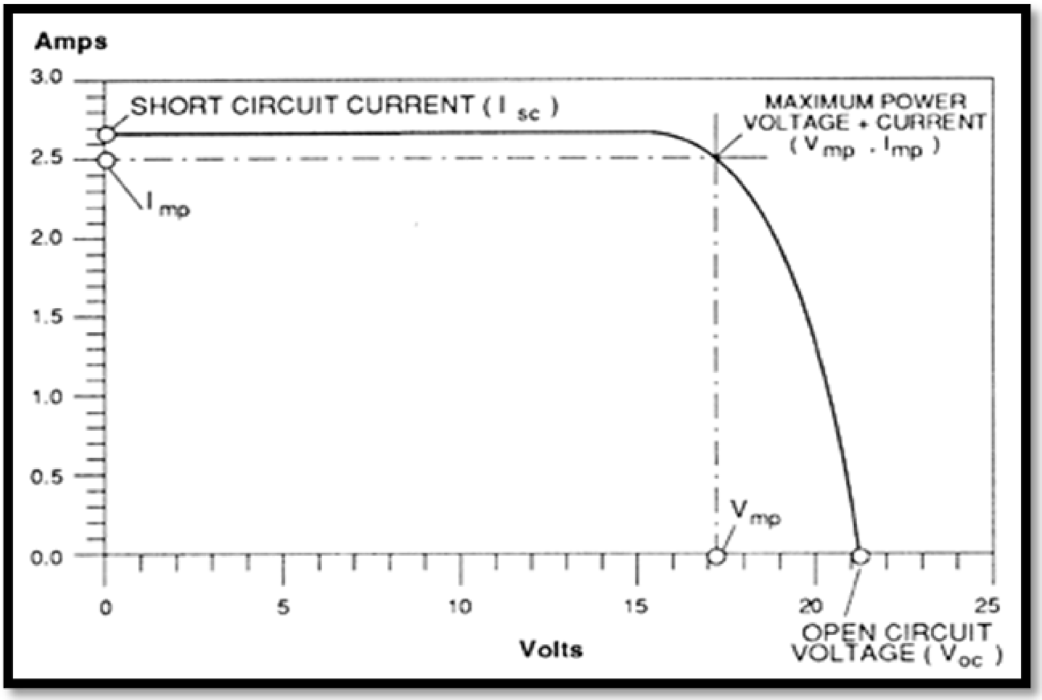


Figure 2-6. IV curve of Solar cell

The point where the power is maximum of a solar cell is the point at which the cell converts the most amount of available power. While the I_{mp} is current at the maximum power point and V_{mp} is the voltage at the maximum power point. On the IV characteristic curve, the position closest to the bend offers the greatest potential for locating the point with the highest power. However, since both the voltage and the current can vary by the variation in temperature, the maximum power point of the solar cell will also change with the change in temperature.

2.5 Building Applied and Building Integrated Photovoltaics

In the case of buildings, there are two methods for installing solar photovoltaic modules: building applied photovoltaics (BAPV) and building integrated photovoltaics (BIPV). BAPV is the process in which we apply photovoltaic modules onto the building with the help of various structures, but BIPV is the technique in which the conventional building material is replaced with the photovoltaic material, and it became a part of the building envelop. BAPV stands for building-applied photovoltaics, and BIPV stands for building-integrated photovoltaics.

2.6 Building-Integrated Photovoltaics

BIPV systems ensure many functions. It is common knowledge that they offer protection against the elements, thermal insulation, noise, and even structural strength (19). In certain configurations, they can also let in natural light and provide a view of the outside world. Most importantly, however, they can generate both thermal energy and electricity. In addition to this, BIPV systems can also serve the purpose of being aesthetically good of the overall appearance of a structure. Because of many benefits that BIPV systems offer, there has been a surge in interest among engineers and architects to research them about both their functionality and their aesthetics. PV modules are now manufactured as standard building products, which has resulted in the creation of an entirely new market for BIPV systems (20). This market segment is one of the photovoltaic industry's most rapidly expanding market segments. By the year 2020, it is anticipated that the number of BIPV installations will have increased at a rate of thirty percent per year. It is anticipated that the installed capacity will be greater than 8000MW by the time the year 2020 comes to a close (21).

2.6.1 Future of Building integrated photovoltaics

As a result of the fact that the BIPV system is an empirical, novel, and encouraging application to achieve net-zero energy and net-zero emission buildings, there is a vast market potential for the BIPVT system all over the world (22). Embedding the PV materials into the structure of building not only eliminates the need for additional space for the installation of photovoltaic systems but also helps to cut down on the additional costs of the structure and generates energy within the building while taking into account the environmental impact of building and its aesthetic value (23,24). In order to accelerate the growth of BIPV systems, a number of nations have created supportive institutional frameworks in their respective nations (25). The current global market size of BIPV systems is nearly 2.3 GW (which is equivalent to less than one percent of the whole world Photovoltaic market) (21), and Europe is constituting the largest shareholder with 42 percent of global market share. This is primarily because of the extra benefits offered in different countries of Europe like Italy, France, and Germany. It is anticipated that the installed capacity of BIPV systems annually across the globe will reach 32.3 GWh by the year 2024 (21). The research that has been done on BIPVs has shown that the systems are capable of satisfying either a portion or the entirety of the energy requirements of buildings (26). This is just one example of how governments in some countries are working to encourage people to adopt this system (24). With all of these advantages, building integrated photovoltaics (BIPV) are quickly becoming more popular in the photovoltaic industry. There are a number of research scholars who have attempted to compile the knowledge about BIPV systems by writing review papers (27–31). In addition, there are a number of articles that have been published on the research and development of BIPV walls (32–34), BIPV roofs(35–38) and shading type BIPV claddings(39–41).

2.6.2 Configurations of BIPV

Diagrammatic representations of the most common types of BIPV system configurations can be found in Figure 2-7 to Figure 2-9, respectively. The BIPV system shown in Figure 2-7 (a) is completely attached the wall of the building. Then Figure 2-7(b) and Figure 2-7(c) depicts a BIPV/T and a BIPV system. One expels the heated air while the second channels the air into air duct located in the fall-ceiling so that it can be used to heat the space. Figure 2-8(a) and Figure 2-8(b) show building integrated photovoltaic (BIPV) applications that make use of semi-transparent PV modules that also bring sun light into the building. A variety of applications may be configured in the windows or wall elements of the building. Roof BIPV and BIPV/T systems are depicted in Figure 2-9(a) through Figure 2-9(d). The system in Figure 2-9(a) is the only one that vents the warm air from back of the PV modules while the other systems use the warm air for indoor heating with the help of ducts. The last one is comparable to system depicted in Figure 2-9(d) which is BIPV/T system that transfers air from the indoor to gap between the PV panels. Two further applications of BIPV that are not represented here are the use of BIPV as shade elements and the use of BIPV systems that also produce hot water and are related to pumps and water storage tanks.

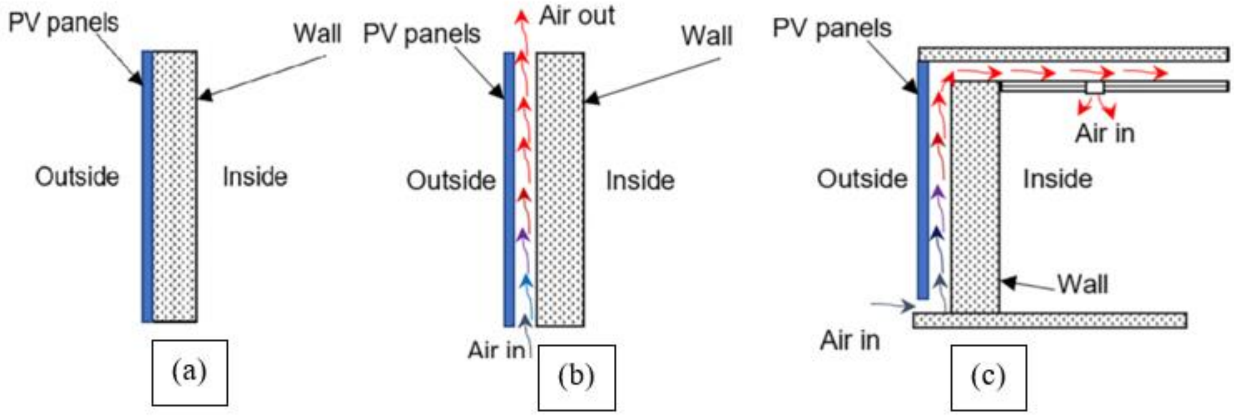


Figure 2-7. (a) BIPV system with PV module attached to the building's wall. (b) BIPV system with PV module having an air gap between skin of building and module. (c) BIPV/T system having gap between wall and photovoltaic module, and a channel to provide warm air into the building.

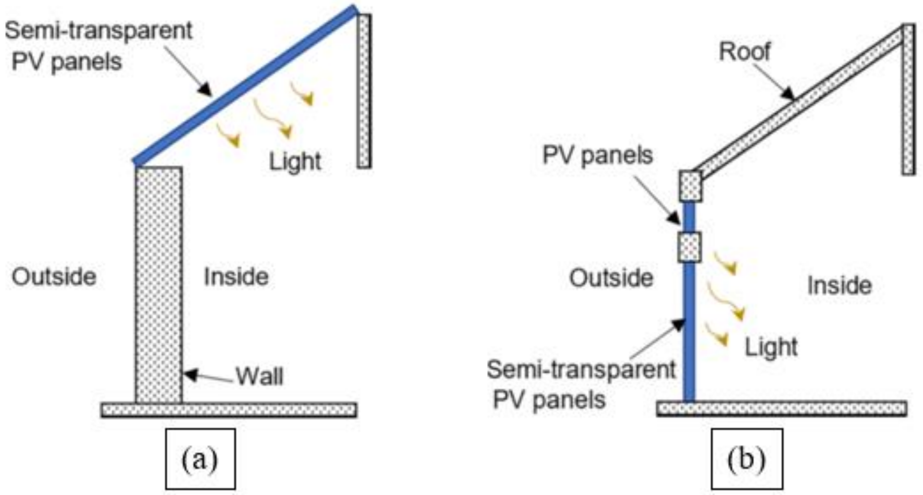


Figure 2-8. (a) BIPV semitransparent roof system with allowing sun light into the building. (b) Vertical BIPV system as semitransparent wall component or windows.

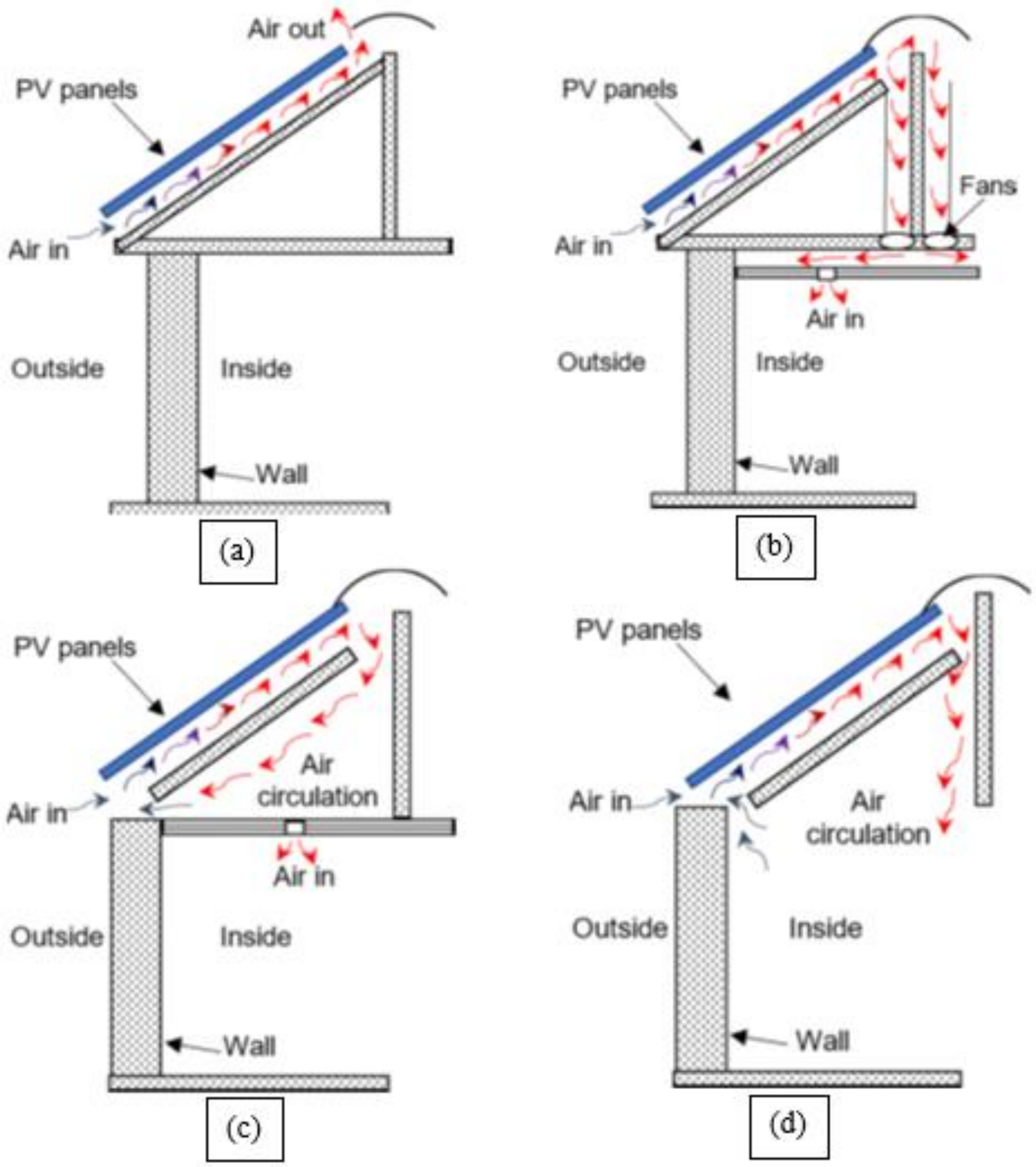


Figure 2-9. (a) BIPV roof system with gap between Photovoltaic module and structure of roof. (b) BIPV/T roof system having gap between Photovoltaic module and structure of roof, and a channel to circulate warm air into building. (c) BIPV/T roof system having gap between Photovoltaic module and structure of roof, which circulate the warm air into the building. (d) BIPV/T roof system having gap between Photovoltaic modules and the structure of roof, which ventilate heated air to building space.

2.7 Trombe Wall

In the 19th century, E.S. Morse was the first person to patent the idea that would later be known as the Trombe wall. In 1957, Jacques Michel and Félix Trombe were the people to develop and popularize the idea. The first home to be constructed with a Trombe wall was finished in 1967 in the French community of Odeillo. The term "classic" or "standard" Trombe wall refers to this wall's straightforward configuration, which was developed with the goal of storing thermal energy from the sun and providing heating for the interior space(42–44). The traditional Trombe wall has a glazed surface, while the outer side of wall is painted with the black color to enhance its radiations absorption rate. The gap is left for the channel between the wall and the glass (45). Figure 2-10 depicts the different ways of operation by using which heating can be done with the help of traditional Trombe wall. The traditional Trombe wall utilizes a massive wall to both absorb and store heat while also capturing radiation from sun by taking advantage of the greenhouse effect that is produced in a cavity. Some of the energy is moved into the building with the help of conduction process, which is referred to as the room. During this time, air with a lower temperature than the rest of the room flows into the cavity from inner side of room through the lower ventilation channel of Trombe wall. The air is then interacted with the wall and become warm, and it flows upward. The warm air is then brought back into the space via the vent located higher up on the wall. Both the vents and the wall itself contribute to the Trombe wall's ability to dissipate heat into the inside. There are a few problems with the trombone wall being so simply set up as to be enumerated below.

(1) Low thermal resistance. When it's cloudy for a while or it gets dark out, a lot of heat escapes the structure because energy is constantly being transferred from the inside to the outside. (42).

(2) When the temperature of the air in the vented layer is higher than that of the storage wall, the air in the ventilated layer is sucked into the storage wall and cooled before being re-injected into the room through the lower vent. Most often during the night in the winter, when the storage wall is cooler than the air in the ventilated layer. This causes a decrease in the room's temperature. (46).

(3) Poor contribution to the aesthetic (47).

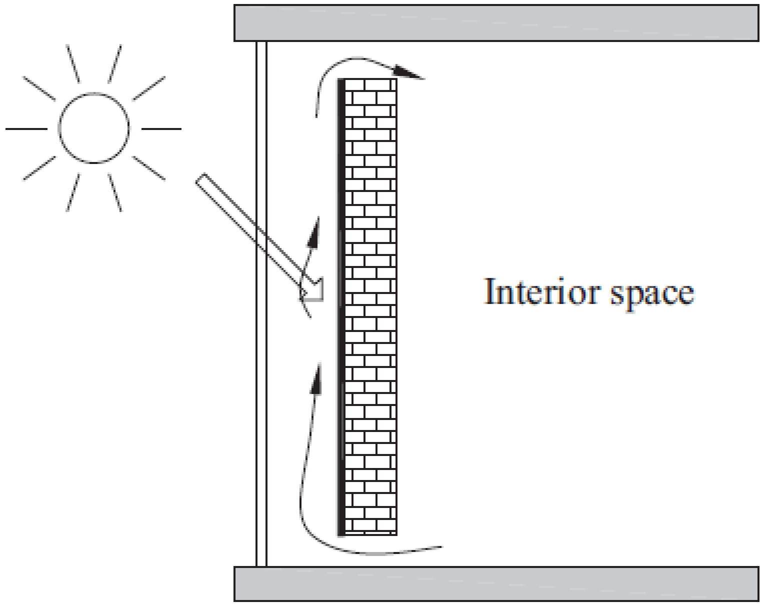


Figure 2-10. Example of a Trombe wall for heating.

The solution that has been proposed to address these deficiencies is to utilize a variety of Trombe wall designs that have been modified. The Trombe wall has been improved upon in a number of ways, resulting in the creation of a number of variants, including composite Trombe walls (42,44), water Trombe wall (48), zigzag Trombe wall (43), trans-wall (49) and fluidized Trombe wall (50,51).

By incorporating solar cells into the classic Trombe wall design, a new type of heating based Trombe wall called the photovoltaic (PV) Trombe wall was developed. The PV Trombe wall is the name given to this latest incarnation of the Trombe wall. (see Figure 2-11). The PV-Trombe wall serves multiple purposes: it generates power, improves the room's ambiance, and helps keep the temperature comfortable. However, this form of Trombe wall creates electricity, which is of higher quality than the thermal energy it provides because of the PV coverage on the glass. (52–54).

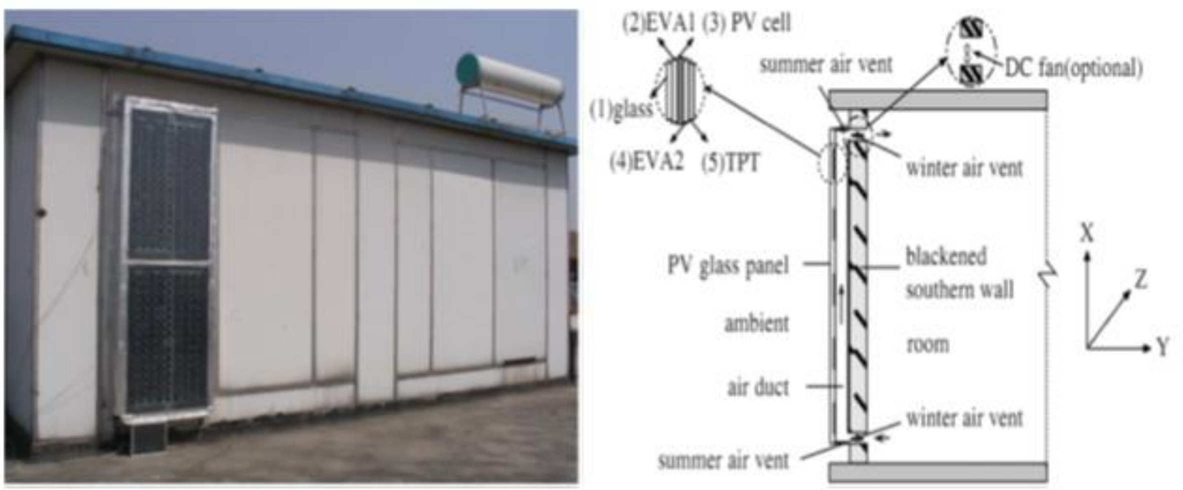


Figure 2-11. Schematic and real prepared building integrated photovoltaics Trombe wall.

2.8 Building Integrated Photovoltaic Trombe wall

Integrating solar cells as Trombe walls is a cutting-edge strategy that can be used to improve the aesthetics of buildings. This concept is gaining steam as more and more people realize how useful it can be in the quest to achieve net-zero energy buildings.

The following characteristics can be found in the PV Trombe wall system:

- The BIPV/T system is mechanically integrated into the structure of the building, and it can be installed as structure of the building by replacing conventional building material.
- The BIPVTW system can supply the building with energy that is both green and clean.
- In addition, this system can supply the building with thermal energy.

Recent research has demonstrated that the individual drawbacks of both the Trombe wall and photovoltaics can be mitigated by employing both technologies together. According to the outcomes of the PVTW mathematical model (53), there was a discernible rise in temperature of 7.7 degrees Celsius. Jie et al. found that the incorporation of DC fans into the PVTW model led to a decrease in both the indoor temperature and the temperature of the PV cells of 0.5 and 1.28 degrees Celsius, respectively (54). Irshad et al.(55) developed a PVTW simulation model for the tropical climate of Malaysia by utilizing TRNSYS software in their project. It was determined how much of an impact air flow rate and the type of glazing had on the PV efficiency, cooling load, and thermal load. The effects of building inclination, orientation, and PV module performance were investigated by Sun et al. (52) under the climatic conditions of Hong Kong. The researchers looked at a variety of cladding materials and cooling loads. Based on the findings, it was determined that photovoltaic panels installed at an angle of 10 degrees had the potential to generate a maximum of 76.8 kWh/m2 of electricity. By incorporating photovoltaic cladding, a cooling load reduction of 34.2% and 51.6% was achieved in relation to the concrete walls and windows, respectively. Jiang et al. (56) evaluated the performance of the PV coverage ratio on a PVTW system under the climatic conditions of Hefei, China, and came to the conclusion that there was an increase in overall PVTW efficiency associated with an increase in cell coverage ratio, but that there was a decrease in the efficiency of individual PV cells.

Recent research has suggested that the heat transfer rate could be controlled to improve the performance of passive heating and cooling by installing venetian blinds (VBs) in the air gap of the TW systems. This would allow for better passive heating and cooling performance (57–59). In the past, the amount of solar radiation that was taken in by the surface of the TW could be altered by modifying the slat angle of the blinds that were attached in the air gap (60). Just by making the necessary adjustments to the slat angle of the blinds, the results demonstrated a significant improvement in the levels of thermal comfort experienced during the hot weather (61). Further research revealed that changing the direction of airflow in VB-TW systems could reduce cooling energy consumption by between 4 and 6% (62).

However, several studies have found that combined Trombe wall Venetian Blinds (TW-VB) systems have several drawbacks during the warm seasons. One of these drawbacks is an increased amount of time spent overheating, particularly when the highly reflective face of the blinds is positioned toward the outside of the building (63). Researchers have developed PV blinds (40), which add a touch of architectural elegance to the exterior environments of buildings while also reducing the amount of energy that is consumed by the buildings themselves, in an effort to mitigate the negative effects of the drawbacks (64). The performance of the PVTW system was evaluated by Ahmed et al. (65), who did so by filling the air channel that lies between the PV panel and the TW with porous material. According to the findings, the utilization of this configuration resulted in an improvement of 0.5 percent in the electrical efficiency and 20 percent in the thermal efficiency. The system's thermal and electrical efficiencies saw a significant boost as a result of the addition of PVTW, which was combined with a nanofluid solution consisting of Al2O3 and water (66). Experimentally, Yu et al. (67) found that by installing PV panels on the TW envelope of a building, it was possible to achieve the highest possible conversion efficiency for the production of electricity throughout the entire year. In addition, they found that the system could provide space heating with efficiencies of 37% in the summer and 12% in the winter, with the added benefit of filtering the air by decaying gaseous formaldehyde.

The photovoltaic cells can be cooled by using redirected moving air or water, depending on the amount of energy that is required by the structure and the production requirements. Over the course of one year, Hu et al. (24) compared the effectiveness of three different types of building-integrated photovoltaic (BIPV) TW systems. These systems included PV cells attached to mass wall (PVMTW), PV cells attached to glass (PVGTW), and as TW with PV blinds (PVBTW). According to the findings, the annual power yield of the PVBTW configuration was approximately equivalent to that of the PVGTW system, which was approximately 20% higher than the PVMTW configuration under the climatic conditions of Hefei (68). Additionally, variable parameters such as the PV blind angle and the inlet airflow rate were utilized to establish which output was optimal in terms of the generation of electricity and the accumulation of heat. According to the findings, the best results in terms of heat gains and electricity generation were obtained with an inlet airflow rate of 0.45 meters per second and a PV blind angle of 50 degrees.

These research studies relied heavily on simulations as their method of data collection and analysis for a considerable portion of the effort. Because of this, it is still important to conduct experimental tests of these technologies in settings that involve the passage of time. In addition, we categories BIPV systems almost exclusively according to either their electrical or thermal performance; nonetheless, it is imperative that we evaluate these systems according to their combined (electrical and thermal) performance. The thermal comfort of the building is improved when BIPV systems are installed as Trombe walls; however, this comes at the expense of the electrical output power of the PV module. Trombe walls are also known as double-skin walls. For this reason, additional research into these systems is still necessary in order to completely comprehend them.

So, in this work BIPV wall system with two alternative configurations was investigated experimentally in Islamabad, which is located at 33.6844 degrees North and 73.0479 degrees East. To carry out the experiments that were part of this research project, three modest wooden rooms were created. Two polycrystalline photovoltaic modules each rated at 10 watts were mounted on the south walls of two separate rooms at a tilt angle of 90 degrees. In one room, the module was embedded as the south wall, which is referred to as building integrated photovoltaic south facade (BIPVSF), and in another room, the module was also installed onto the south wall, but in the form of a Trombe wall, which is referred to as building integrated photovoltaic Trombe wall. Both configurations are referred to as building integrated photovoltaic walls (BIPV). For making a comparison, the third room was prepared, but it did not contain any PV modules, instead its south side wall was also made of wood. The individual electrical performance, thermal performance, and subsequently the combined (electrical and thermal) performance of both the BIPVSF and the BIPTW systems were proved using experiments.

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Chapter 3

Research Methodology

The experiment of this study was conducted at Islamabad, capital city of Pakistan in March 2022 (33.6844° N, 73.0479° E). This city has a great potential for solar energy as daily basis available solar radiation intensity data shows that the daily direct normal irradiance (DNI) is 4.5-5 kWh/m^2, the daily global horizontal irradiance (GHI) is 4.75 kWh/m^2, and the daily potential for electricity generation by using solar photovoltaic is 4.5 kWh/kW [1]. These numbers indicate that the city has a great potential for solar energy. According to the Koppen climate classification method, Islamabad has a climate that is classified as Cfa, which is known as a humid subtropical climate [2]. In Islamabad, the annual temperature averages out to be 21.3 degrees Celsius, or 70.34 degrees Fahrenheit. The average annual precipitation totals 1201 millimeters or 47.23 inches here [3].

3.1 Experimental setup

For this investigation, three modest wooden rooms were constructed out of sheets of wood, each with a wall thickness of 0.5 inches. All the rooms have the same measurements when viewed from the interior, which are (length = 1 foot, width = 1 foot, and height = 1 foot), as demonstrated in Figure 3-1. All the rooms are airtight and well insulated from inside and outside. The major difference in all the rooms is in the design of their south side wall.

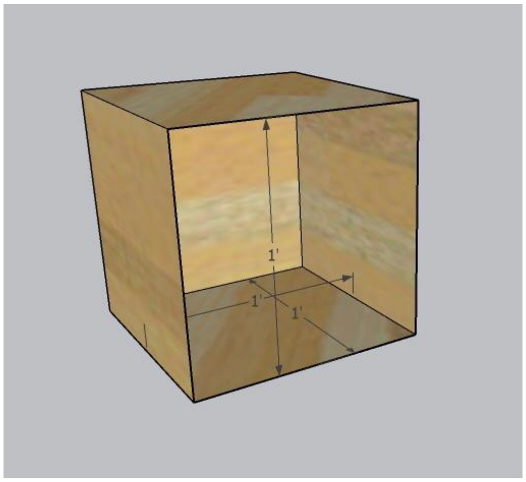

Figure 3-1. Dimensions of wooden room.

Two of the rooms each had solar photovoltaic modules installed, and the south wall of the third room was constructed entirely of wood so that it could serve as a reference room. Because we were embedding solar PV modules into the south walls of the rooms, the design of the walls on the south side of the two rooms was determined by the size of the solar PV module that was utilized for this study. In this particular study, two polycrystalline solar PV modules were utilized, both of which had identical technical parameters. Table 3-1 contains the specification detail of the PV modules. Both photovoltaic (PV) modules were installed in each room at a tilt angle of 90 degrees.

Table 3-1. Specification of solar PV module

Parameter	Unit	Parameter	Unit
Cell type	Polycrystalline silicon	Open circuit voltage	21.5
Maximum output power	10 watts	Short circuit current	0.65
Operating Voltage	17	Number of solar cells	36
Current	0.59	Operating Temperature	25 °C

In addition to having a solar panel mounted on the south side wall of each of these two rooms, the south side walls of each of these rooms were configured differently, and the rooms were named according to the configuration of the south side wall of their respective room. The specifics are discussed in the following section.

3.1.1 Building integrated photovoltaic south façade (BIPVSF) room

Within the framework of this system, the room's layout is conceived based on the idea of a building-integrated photovoltaic system. The sheets of wood were used for the preparation of walls of the room except south side wall. South side wall of this room was replaced with a polycrystalline solar PV module as shown in Figure 3-2. Because of this transformation, the room was given the name building integrated photovoltaic south façade room. For the measurement of electrical power output, the positive and negative terminals of module were drawn out of the room through side wall. As can be seen in Figure 3-3 seven thermocouples of the K type were painstakingly placed in various strategic locations to conduct research on the thermal characteristics of the BIPVSF room. On the front side of the PV module, two thermocouples were placed to measure the front surface temperature of module, and on the back side of the module, two thermocouples were placed to measure the temperature on back surface of the PV module. To get an accurate reading of the temperature inside the room, three thermocouples were placed in the exact center of the room. One was installed on the upper side of the room, another in the middle of the room, and the third one was installed close to the lower part of the room.

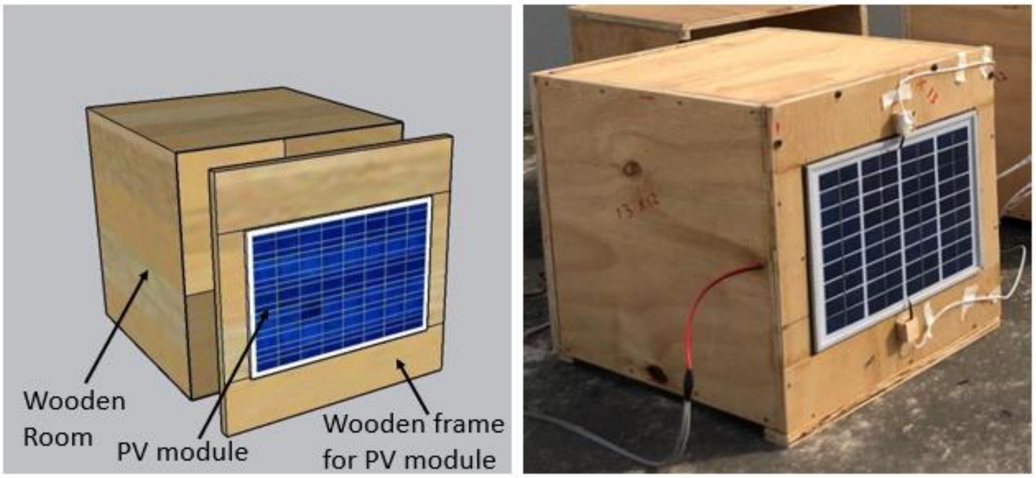

Figure 3-2. Picture of 3d model and actual prepared BIPVSF room.

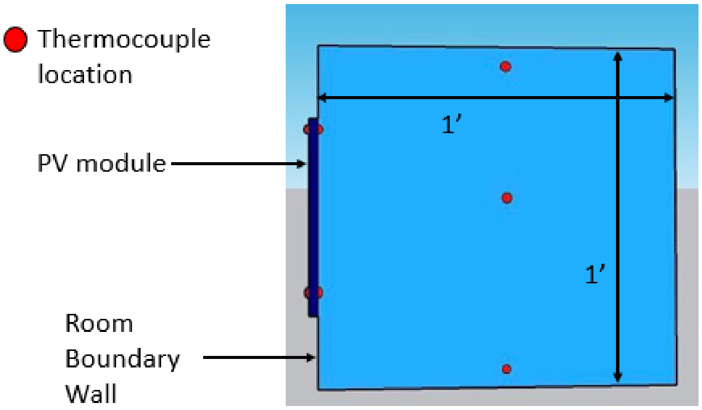

Figure 3-3. 2D model of BIPVSF room with location of installed thermocouples.

3.1.2 Building integrated photovoltaic Trombe wall (BIPVTW) room

In BIPVTW system, the structure of this room was designed according to the phenomena of Trombe wall, and that is why it was named as Building integrated photovoltaic Trombe wall. Solar PV module was embedded in the south side wall of the room with help of a wooden frame as illustrated in Figure 3-4. Two vents (vent1 and vent2) were prepared in that wooden frame for the air circulation. One was on the upper side of south wall and second was on the lower side of south wall. These two vents were used for the air ventilation from the room and then back to the room. A 5mm glass was installed in front of PV module with 1 inch gap between PV module and glass. This gap was provided with the help of another small wooden frame. The upper and lower side slits of this small wooden frame were moveable and used as outer vents (vent3 and vent4) for the outside air ventilation purpose if needed. Electrical terminals of PV module were drawn out from the side wall of the BIPVTW room to measure the electrical parameters of PV module.

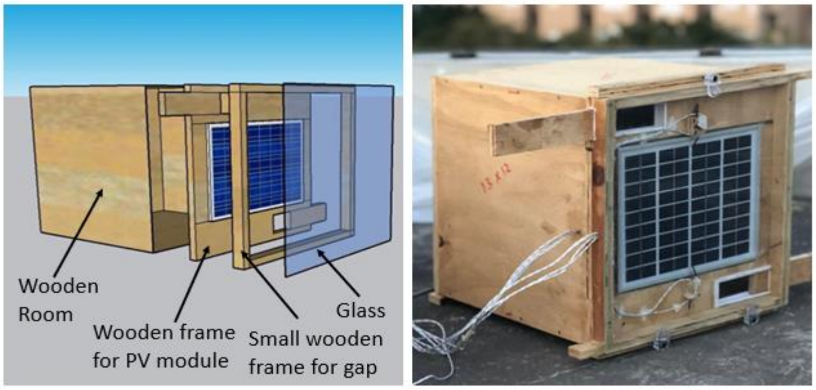

Figure 3-4. Picture of 3d model and actual prepared BIPVTW room

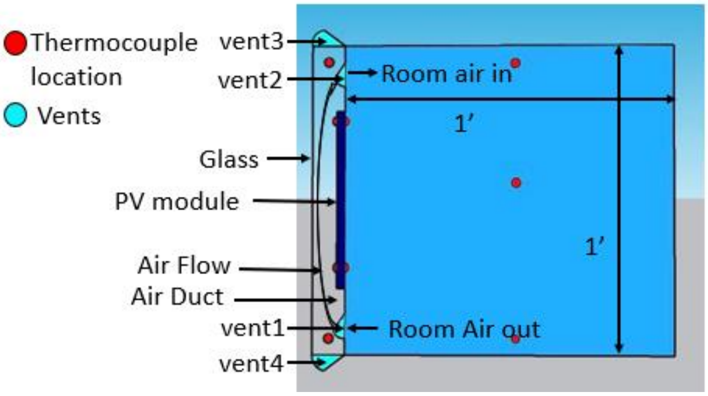

Figure 3-5. 2D model of BIPVTW room with location of installed thermocouples and vents.

Total Nine K-type thermocouples were installed in BIPVTW room model at different specific places for temperature measurement. Four of them were installed in the channel between glass and PV module (two for module front side temperature measurement and two for the measurement of air temperature in the channel). The remaining five thermocouples were installed inside the room (two for module back surface temperature measurement and three for the measurement of air temperature within the room). Details of vents and thermocouples are shown in Figure 3-5.

3.1.3 Reference wooden Room

A reference wooden room was prepared in which the south side wall of the room was also prepared of the wood along with the other walls of the room as shown in

Figure 0-6. This room was prepared to do the comparative analysis and to calculate the heat gain of BIPVSF room and BIPVTW room with reference to this room. In this room, three thermocouples were installed in the center of the room to get the room’s temperatures. One was installed on the upper side; second one was in the middle and third one was near to the base of the room as shown in Figure 3-7.

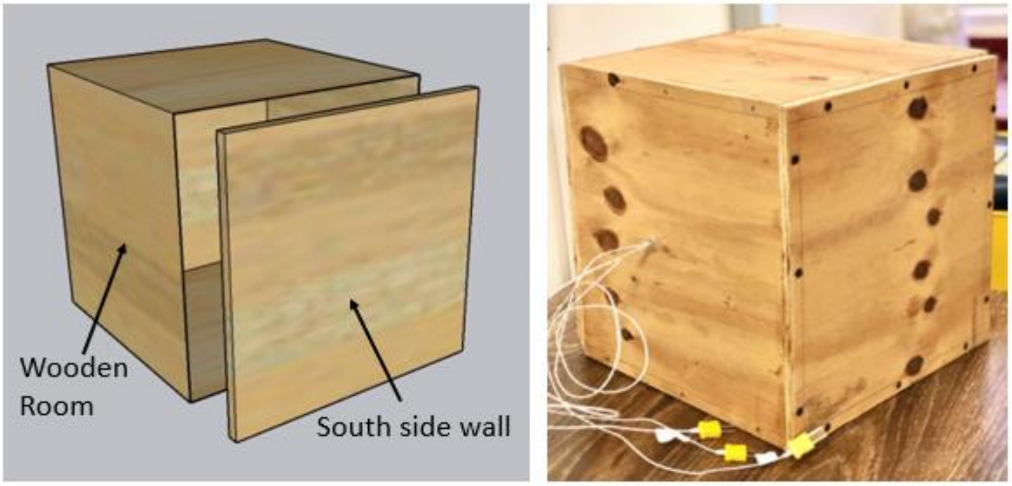

Figure 0-6. Picture of 3d model and actual prepared reference wooden room.

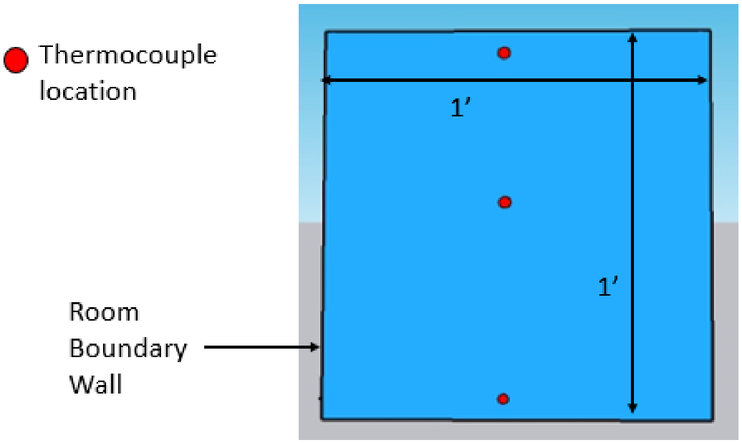

Figure 3-7. 2D model of Reference wooden room with location of installed thermocouples.

3.2 Data Acquisition Station

To read and store the data of electrical and thermal parameters such as voltage, current and temperature of prepared systems, an automatic data acquisition station was prepared and integrated with the system to collect the data.

3.2.1 Electrical data logger

To analyze the electrical parameters of BIPVSF module and BIPVTW module, an Arduino based data logger was designed to store the data. At first, load optimization of both PV modules was done by using rheostat and testing PV modules at different resistive loads by varying the values of resistance on a clear day. Then ceramic resistors of optimized value (20 Watts 56 ohms for both modules) were used, and voltages of both modules were measured across these resistors. To measure the real time values of voltage, voltage sensors were utilized which are known as digital voltmeters. An Arduino UNO is used, and voltage sensors were integrated to it to store the values. SD card module was also integrated with the Arduino to save the real time data in Sd card. The whole circuit was prepared on breadboard and the circuit diagram is shown in Figure 3-8.

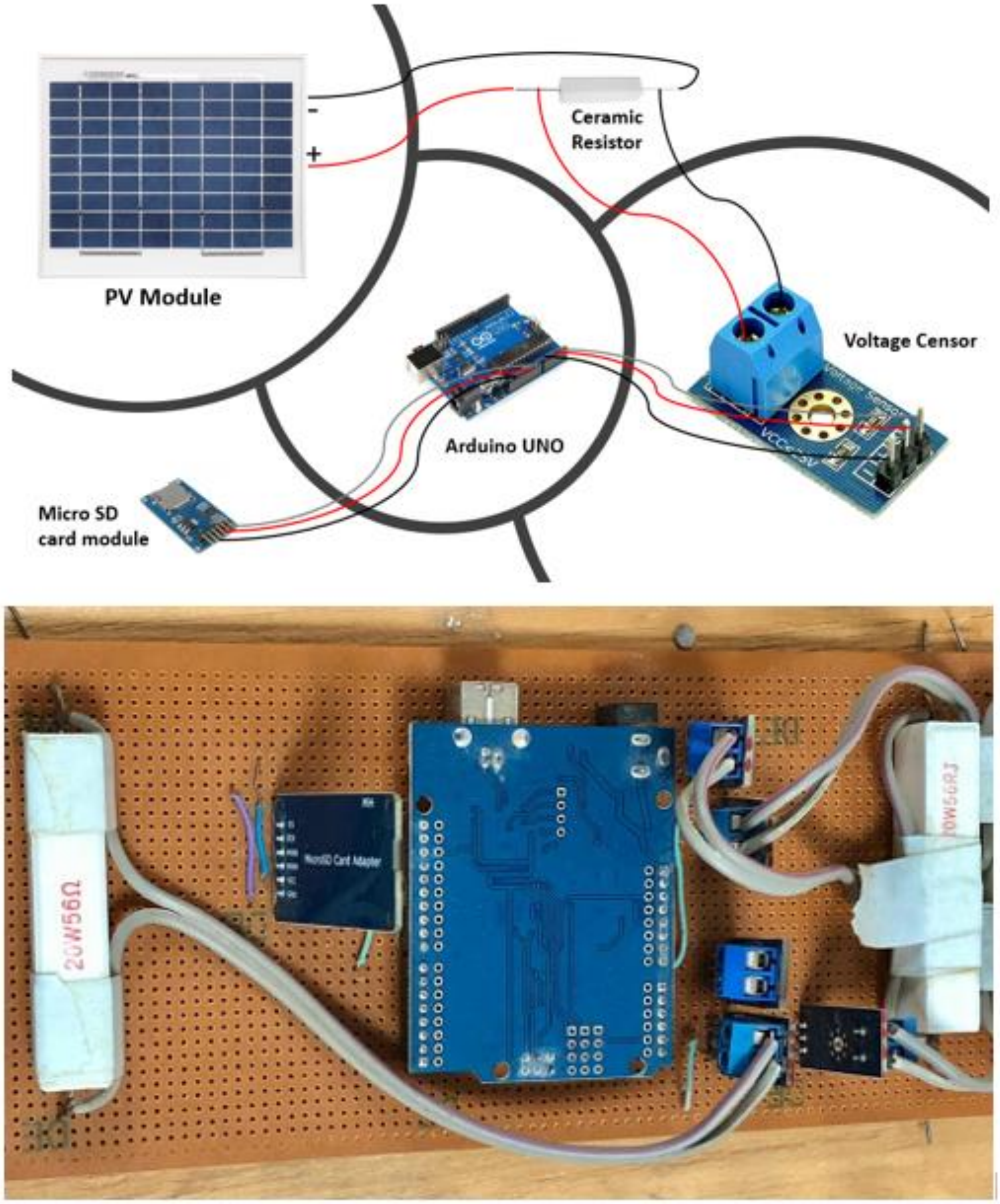

Figure 3-8. Schematic diagram and picture of real prepared electrical data logger.

By using this data logger, real time values of voltages were recorded across the resistors. The values of current were then calculated by using the ohm's law as mentioned in 1.

$$\mathrm{V} = \mathrm{I} \times \mathrm{R} \qquad 1$$

Where V is the voltage, I is current, and R is resistance.

By rearranging the equation, the value of current can be found.

$$\mathrm{I} = \mathrm{V} \div \mathrm{R} \qquad 2$$

The output powers of modules were calculated using the equation 3.

$$\mathrm{P} = \mathrm{V} \times \mathrm{I} \qquad 3$$

To calculate the daily total power generation of PV module, the area under the curve was calculated using origin software for that specific day.

The instantaneous electrical efficiencies of modules were calculated by using the equation 4.

$$\eta = \left(\frac{\mathrm{P}}{\mathrm{A} \times \mathrm{G}}\right) \times 100 \qquad 4$$

Where P is the output power of the module, A is the area, and G is the irradiance.

3.2.2 Thermal Data logger

Two TM500: 12-Chanel datalogging thermometer of EXTECH company with 12 channels each were used to read and record the values of temperature from all the thermocouples installed in the systems. EXTECH 12-chanel thermal data loggers can be used to measure the temperature up to different ranges depending upon the type of thermocouple used with it. As in this study, type K thermocouples were used, so temperature can be measured ranges from -100 to 1300°C with a basic accuracy of ±0.4% reading (+1.8°F/+1°C). The data can be recorded from all 12 channels simultaneously onto an SD card in excel format for further analysis. Both data loggers were calibrated as well by using thermocouple data logger calibrator of EXTECH company so that we can get the accurate values of temperature.

The heat gain of both BIPVSF system and BIPVTW system was then calculated by using the equation 5.

$$Q = m \times Cp \times \Delta T \qquad 5$$

$$Q = m \times Cp \times (T2 - T1) \qquad 6$$

Where m is the mass of air, Cp is the specific heat constant of air and T2 is the temperature of BIPVSF system and BIPVTW system and T1 is the temperature of the reference wooden box.

Mass of air was calculated by using equation 7.

$$m = V \times \rho \qquad 7$$

Where V is the volume and ρ is the density of air.

Volume = 0.0283m³, density = 1.16kg/m³ (as the temperature of air ranges from 35°C to 47°C during the experimentation) and Cp = 1.006kJ/kg-K.

The daily total energy gain was calculated by finding the area under the curve using origin software.

Thermal efficiencies of both systems were calculated using the equation 8.

$$\eta = (\frac{Q}{A \times G}) \times 100 \qquad 8$$

Where Q is the heat gain, A is the area, and G is irradiance.

3.2.3 Climate Data

Global horizontal irradiance (GHI) and ambient temperature data used for the study is taken from the tier 1 metrological weather station installed on the rooftop of the center where experimentation was performed.

Summary

At first Prototypes of two recommended systems BIPVSF and BIPVTW were prepared by using wood sheet and polycrystalline silicon solar PV modules for experimentation purpose. Secondly, Instrumentation was done precisely. After that data acquisition station was prepared to read and record the electrical and thermal parameters of both systems. To read and record electrical parameters of system, a self-designed data logger was designed according to the requirement while for study of thermal parameters a 12-channel datalogging thermometer of EXTECH company was used. Equations used for this study were explained above. Climate data used in this study was taken from a tier-1 weather station installed at the rooftop of the center where experimentation was performed.

References

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Chapter 4

Results and Discussion

The electrical and thermal performance of both building integrated photovoltaic south façade (BIPVSF) room and building integrated photovoltaics Trombe wall (BIPVTW) room with respect to the reference room was investigated at the location of Islamabad, Pakistan. The experiment was carried out from March 21st, 2022, to March 23rd, 2022. The Climate data (ambient temperature and global horizontal irradiance (GHI)) of 21st March 2022 to 23rd March 2022 is shown in

Figure 4-1.

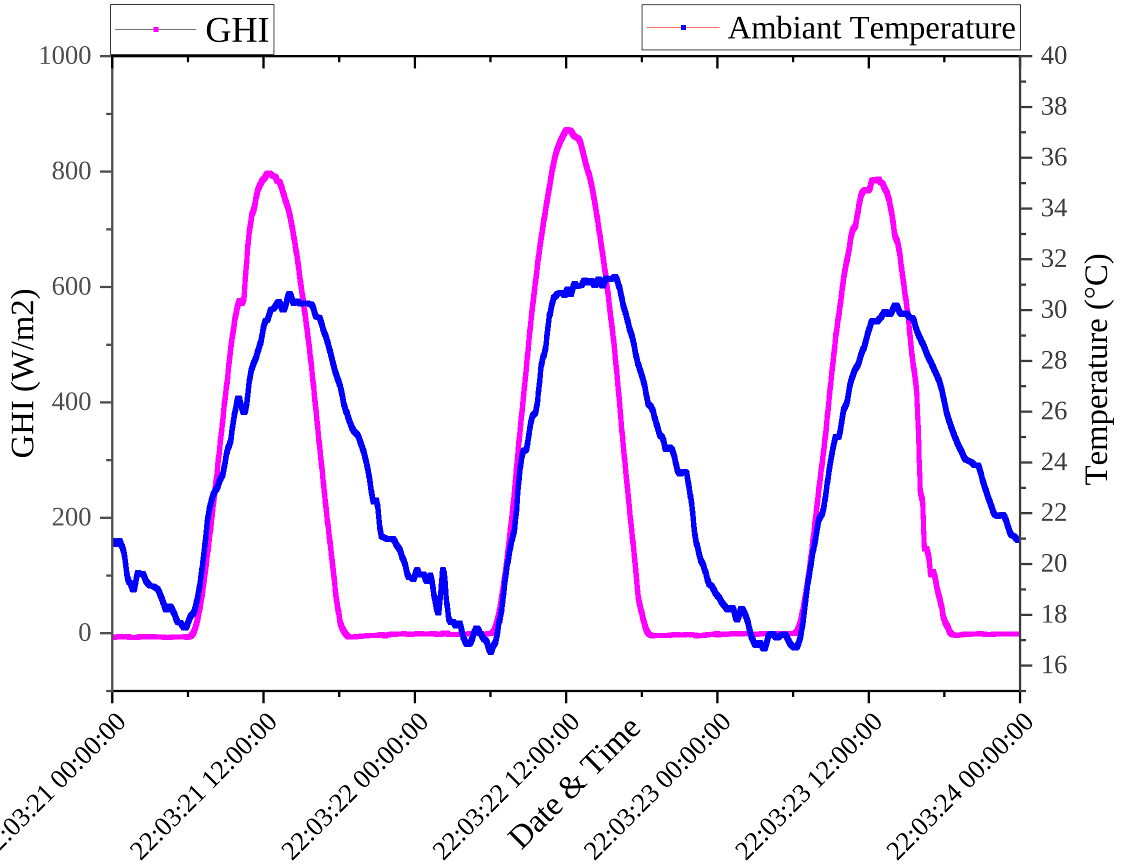

Figure 4-1. Ambient temperature and global horizontal irradiance (GHI).

During the testing days the weather was fine and clear. The daily average values of different elements of climate are mentioned in Table 4-1 and the weather data was provided by the tier 1 weather station installed besides the experiment location. From the table we can see that the average GHI and temperature was higher on 22nd of March as compared to 21st and 23rd of March.

Table 4-1. Daily average values of climate elements for testing days.

Date	GHI (W/m²)	T (°C)	RH (%)	Barometric pressure Avg.	WS (m/s)
21st March	480	23.8	58.2	964	1.4
22nd March	536	24.1	49.1	954	1.9
23rd March	464	23.2	46.8	953	1.6

In case of BIPVTW system winter vents (vent1 and vent2) were opened for the flow of air but summer vents (vent3 and vent4) remain closed during the days experimentation. Cold air flowed from room through vent1, and heated air came back to the room through vent2 by natural ventilation. There was no source of forced ventilation was used in BIPVTW system. The electrical and thermal data measured from the experimentation was used to analyze the energy performance of BIPVSF room and BIPVTW room.

4.1 Systems temperatures

Figure 4-2 indicates the behavior of BIPVSF module temperature, BIPVTW module temperature and ambient temperature for all three testing days. In general, the temperature of modules increases from morning and reach to their maximum level at around 1 p.m., and after that, their slopes start moving downward. This trend of temperature is mainly due to the trend of solar radiations. As in first half of the day the solar radiations intensity increases continuously with the time, the temperature of modules also increases till noon and after that as solar radiation intensity start decreasing, the temperature of the modules also decreases. Similarly, Mamun et al. reported that increase in every 100 W/m^2 irradiance level raises temperature of PV cell by 7.52°C in indoor condition and by 5.67°C in outdoor condition[1].

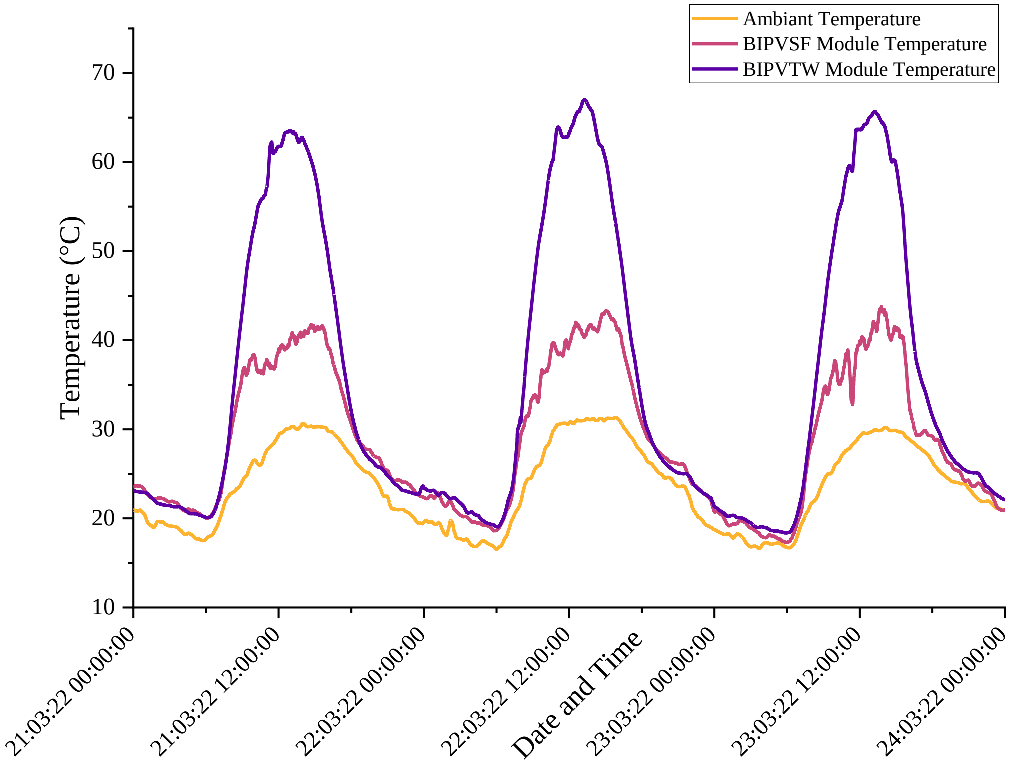

Figure 4-2. Temperature of BIPVSF module, BIPVTW module and ambient temperature for all three testing days.

However, as the solar irradiance started to increase, the module temperature of BIPVTW module rises more rapidly with the time as compared to the BIPVSF module and recorded temperature of BIPVTW module is higher than that of BIPVSF module for all the three testing days. In a similar study Irshad et al. stated that the module temperature of PVTW quickly rises above the ambient temperature when solar flux is high[2]. It is noted that the temperature of the BIPVSF module remain lower than that of BIPVTW module and as the temperature of modules rises, the difference between the temperature of modules also increases until temperatures reach to their maximum level. The daily highest temperatures of BIPVTW module, BIPVSF module and their difference for 21st, 22nd and 23rd of march are mentioned in the Table 4-2.

Table 4-2. daily highest ambient temperature, BIPVTW module temperature, BIPVSF module temperature and their difference.

Date	Ambient Temperature	BIPVTW module Temperature	BIPVSF module Temperature	Difference
21/03/2022	30°C	63.5°C	41.7°C	21.8°C
22/03/2022	31°C	66.8°C	43.3°C	23.5°C
23/03/2022	30°C	65.6°C	43.7°C	21.9°C

The highest temperature of BIPVTW module and BIPVSF module was 66.8°C and 43.3°C respectively recorded on 22nd of March and their difference was 23.5°C.

Figure 4-3 shows the ambient temperature and the internal room temperatures of all the three rooms for the three testing days. It is clear from the figure that during the daytime the internal room temperature of BIPVTW room is higher than that of BIPVSF room and the temperature of BIPVSF room is higher than that of reference wooden room. The higher is the temperature of the PV module, the higher is the internal temperature of the room. Azhar et al. also concluded in his results that use of glass cover on the front side of the modified Trombe wall causes rise in the temperature of the solar module, which in result reduce the electrical efficiency of the system but enhance the room temperature[3].

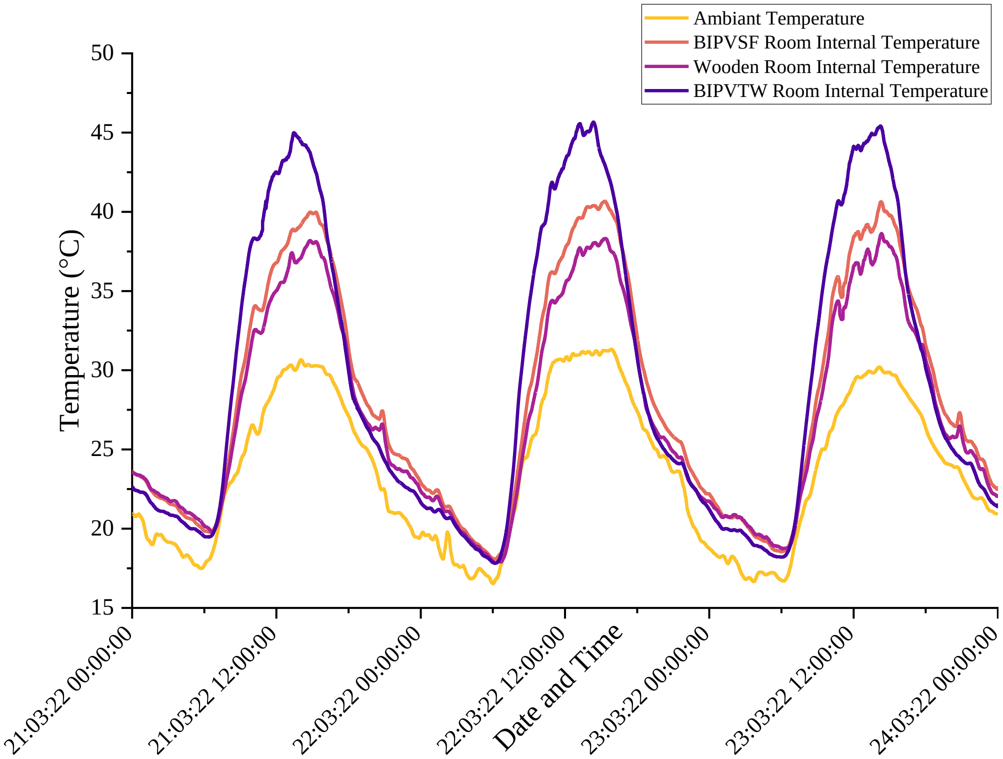

Figure 4-3. Internal temperature of all (BIPVSF, BIPVTW, wooden) rooms and ambient temperature.

4.2 Electrical Performance

The output power of a PV module majorly depends upon the quantity of solar radiation fall on the PV module surface[4]. Optimized tilt angle and azimuth angle are used to get the maximum amount of solar radiation on the surface of PV module[5]. While studying building integrated photovoltaics wall, there are restriction of tilt angle as in most cases walls can only be installed at 90° tilt angle except some special cases. In this study the tilt angle of PV modules was 90° and the azimuth angle was taken as true south.

The daily electrical power output of BIPVSF module and BIPVTW module and its variation throughout the day from 21st March to 23rd March along with the global horizontal irradiance is shown in the Figure 4-4. This figure demonstrate that the electrical power output of both modules follows the trend of solar irradiance where power increases with the increase in irradiance and reach its maximum value by 12pm and then start declining with the time[6]. Moreover, it is clear from the Figure 4-4 that electrical power output of BIPVSF module is more than that of the

BIPVTW at every point of the day because of the presence of glass in case of BIPVTW system[3]. This glass reflects a portion of solar radiation coming towards BIPVTW module which in results lower its output power. Furthermore, the presence of glass elevates the temperature of BIPVTW module more than that of the BIPVSF module as shown in Figure 4-2.

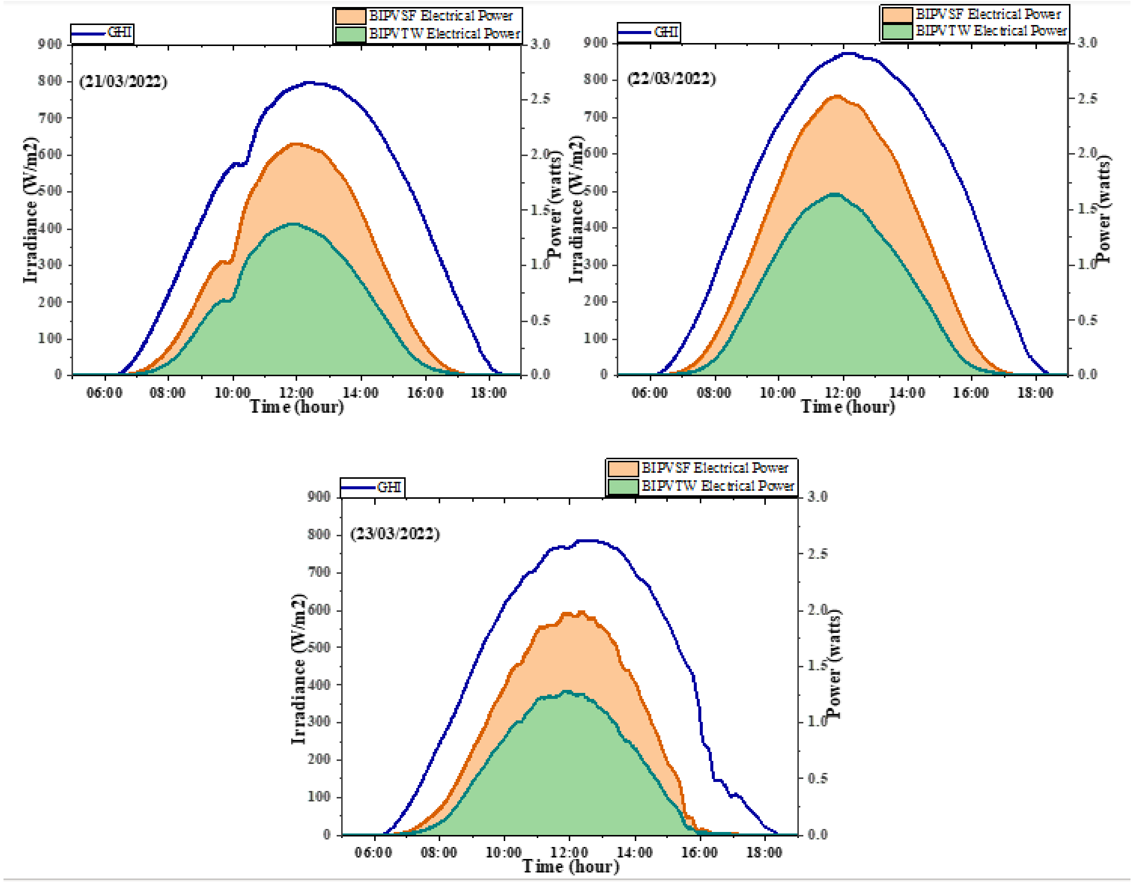

Figure 4-4. Daily irradiance and electrical power output of BIPVSF module and BIPVTW module.

This increase in temperature of BIPVTW module also cost decrease in the electrical power output. Figure specify that there is a little variation in the electrical power output of both BIPVSF module and BIPVTW module for all different days of experiments majorly depending on the solar irradiance[7]. Maximum value of irradiance, the corresponding electrical power output of BIPVSF module and BIPVTW module of each testing day is mentioned in Table 4-3. It is understandable from the table that the more the value of irradiance, the more was the electrical power output of the modules. As mentioned in the Table 4-3, on 22nd of march the maximum irradiance was higher with the value of 872 W/m² among all three testing days so the electrical output powers of both BIPVSF module and BIPVTW module were also higher on that day with the values of 2.52 watts and 1.64 watts respectively.

Table 4-3. Maximum values of Irradiance, BIPVSF module electrical power output and BIPVTW module electrical power output of each test day.

Date	Maximum Irradiance (W/m²)	Maximum BIPVSF electrical power output (watts)	Maximum BIPVTW electrical power output (watts)
21/03/2022	795	2.10	1.38
22/03/2022	872	2.52	1.64
23/03/2022	787	1.98	1.28

Figure 4-5 depicts the daily instantaneous electrical efficiencies of BIPVSF module and BIPVTW module for 21st, 22nd and 23rd of March from 8:30 to 16:30. It is shown that the electrical efficiency of the PV module installed as south facade is higher than that of the module which is installed as Trombe wall. The reason why the electrical efficiency of the BIPVSF module is lower than that of the BIPVTW module can be attributed to the presence of glass and higher temperature of PV cells of BIPVTW module. The maximum efficiency of BIPVSF module and BIPVTW module was 6.02% and 3.96% on 22nd march.

Daily electricity generation of BIPVSF module, BIPVTW module and their difference is shown in Figure 4-6.

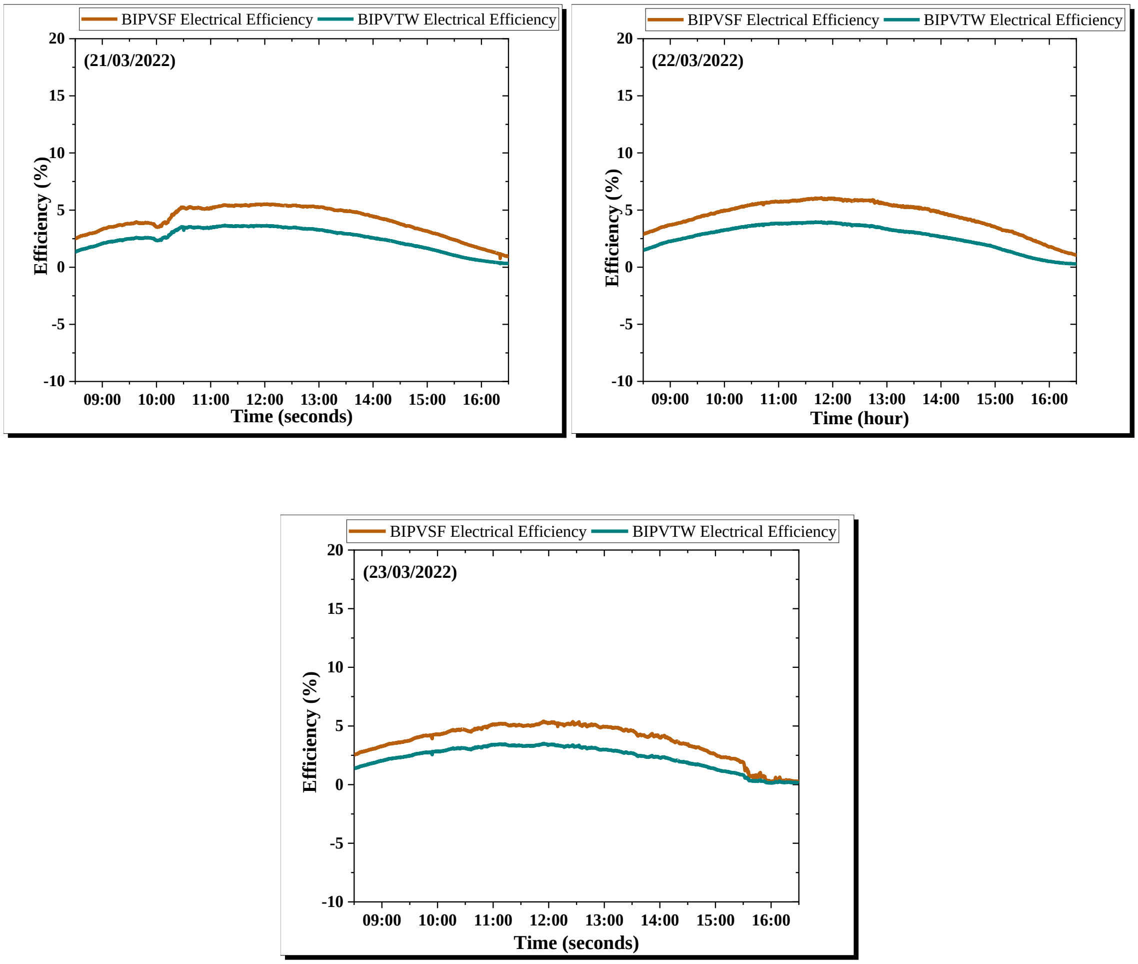

Figure 4-5. Daily Electrical Efficiency of BIPVSF module and BIPVTW module

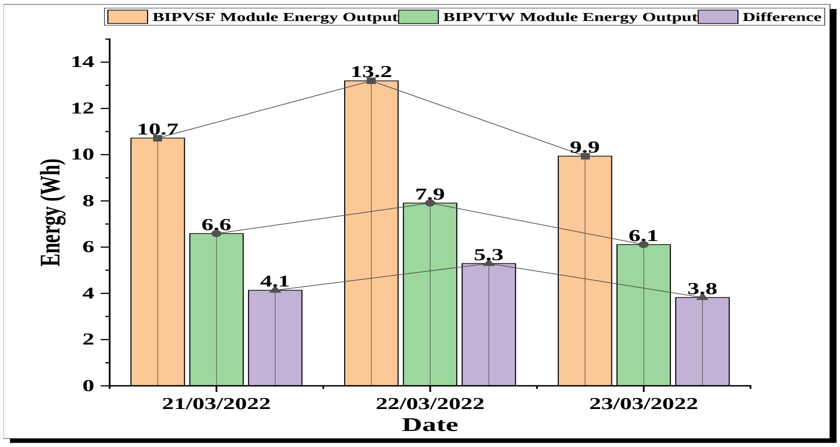

Figure 4-6. Daily total electrical energy output of BIPVSF module and BIPVTW module and their difference.

4.3 Thermal Performance

The heat gain using the proposed BIPVSF and BIPVTW system along with the electricity generation reduces the requirement of energy to heat up the building at the same time and it replaces the energy produced by fossil fuels with clean energy which influence positive on the environment. Under the similar weather conditions as shown in the

Figure 4-1, the reference wooden room is selected to do the comparative analysis and to evaluate the thermal performance of both BIPVSF and BIPVTW system. The summer vents (vent1 and vent2) remain open during the experimentation for BIPVTW system for air ventilation.

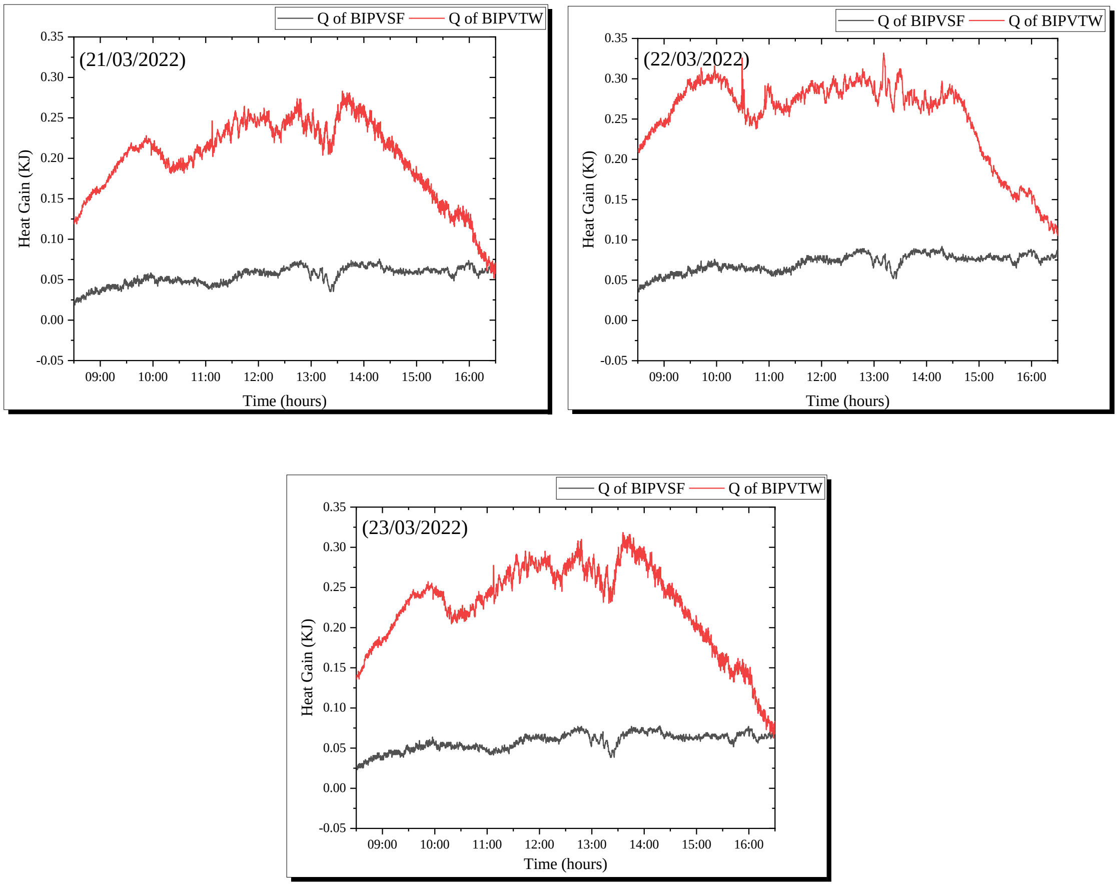

Figure 4-7. Daily instantaneous heat gain of BIPVSF and BIPVTW systems.

Figure 4-7 shows the daily instantaneous heat gain of BIPVSF system and BIPVTW system from 8:30 to 16:30 achieved by the natural ventilation of air within the systems for all the three testing days. It is clear from the Figure 4-7 that during the daytime the instantaneous heat gain of BIPVTW system is significantly higher than that of the BIPVSF system. In a similar study Azhar et al. reported in his results that the presence of glass in front PV module increases the PV cell temperature, which in result increase the heat gain of system[8]. By the start of the day instantaneous heat gain of BIPVSF systems started increasing gradually but a sharp increase in instantaneous heat gain of BIPVTW system can be seen in the fig till 14:00 and then it starts decreasing. Figure 4-8 depicts the daily instantaneous thermal efficiency of BIPVSF system and BIPVTW system. The results shows that daily average thermal efficiencies of BIPVSF system are 9.89%, 11.64% and 11.66 on 21st to 23rd of March, while those of BIPVTW system are 34.66%, 39.88% and 40.74%.

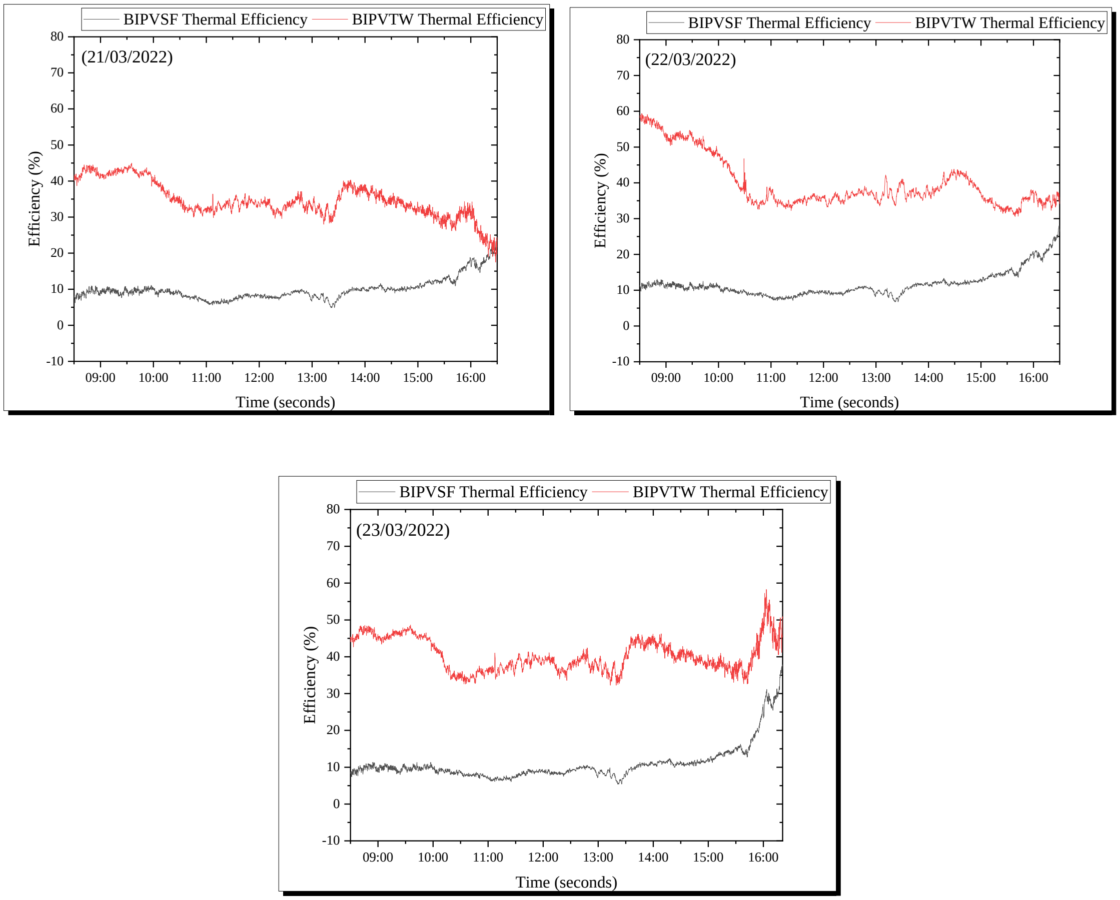

Figure 4-8. Daily instantaneous thermal efficiencies of BIPVSF system and BIPVTW system.

The daily statistics of total heat gain are shown in Figure 4-9. The values of daily total heat gain of BIPVSF system are 190KJ, 261KJ and 204KJ on 21st, 22nd and 23rd of March respectively while the values of heat gains of BIPVTW system are 611KJ, 817KJ and 694KJ. Through calculation the daily total heat gain of BIPVTW system is on average 220% more than that of the BIPVSF system.

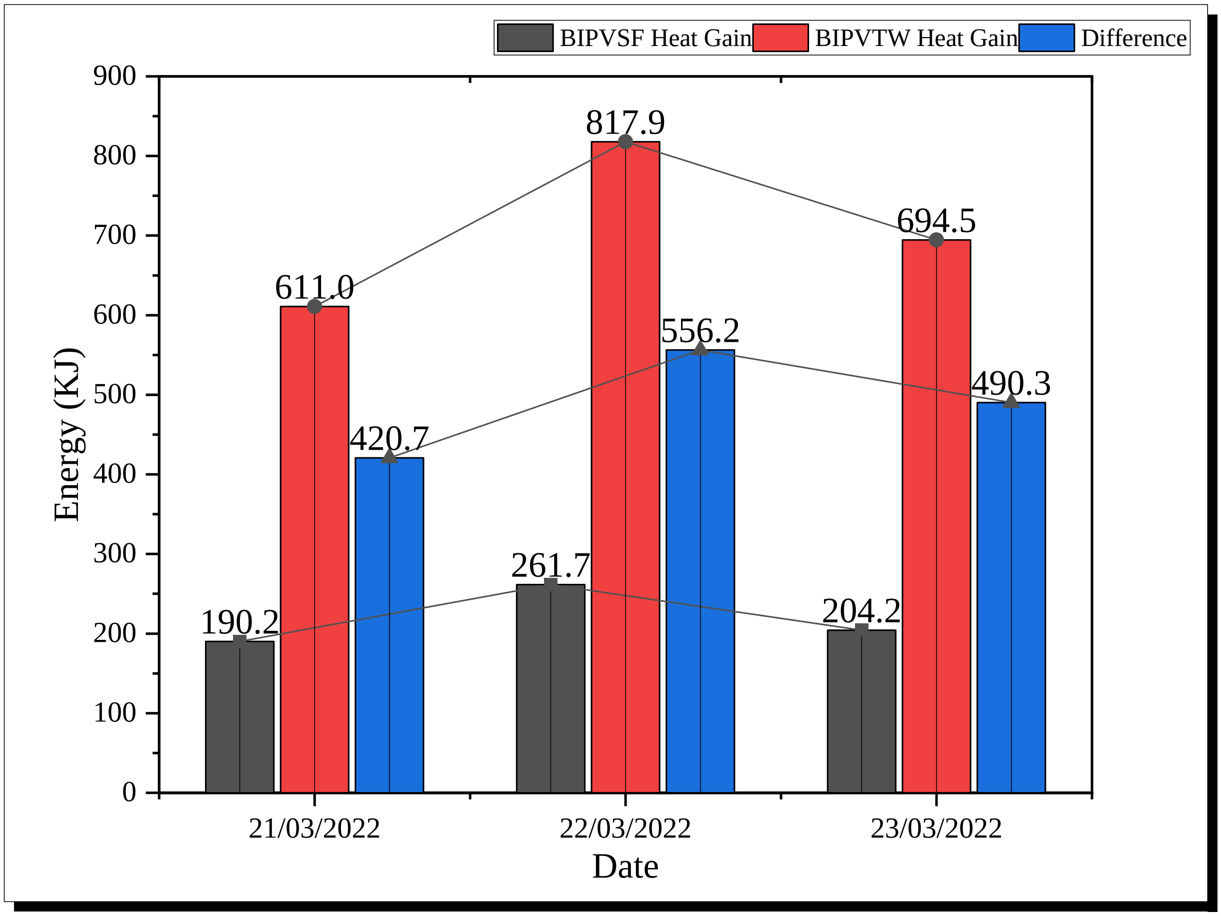

Figure 4-9. Daily total heat gain of BIPVSF system, BIPVTW system and their difference.

4.4 Combine Performance

The combine (electrical and thermal) performance of both BIPVSF system and BIPVTW system is calculated by converting electrical powers and thermal energies of the systems into same unit and then added up to see their combine effect.

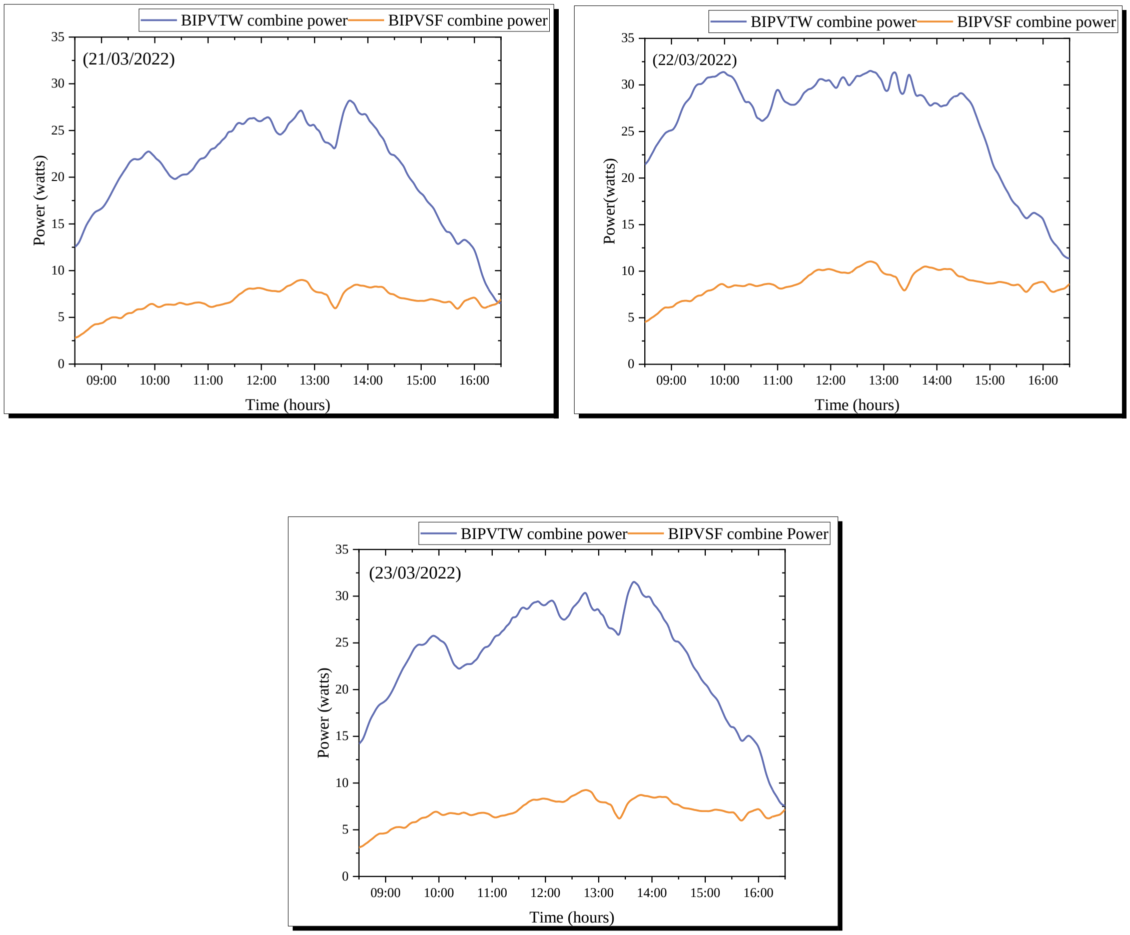

Figure 4-10. Daily combine electrical and thermal power output of BIPVSF and BIPVTW systems.

Figure 4-10 shows the combine power output of BIPVSF system and BIPVTW system. It is clear from the Figure 4-10 that the combine electrical and thermal power output of BIPVTW system is greater than that of the combine power output of BIPVSF system. Even though the daily electrical power output of the BIPVTW system for all the testing days was compromised up to 39% on average as shown in Figure 4-6 but the combine effect of both electrical power and thermal energy gain of BIPVTW system yield on average 64% more output power.

The instantaneous combine efficiencies of BIPVSF system and BIPVTW system are illustrated in Figure 4-11. It was found from the calculation of results that the daily average combine efficiencies of former were 12%, 13.9% and 13.6% on 21st, 22nd and 23rd of March while those of the later were 35.9%, 41.2% and 41.9%. The daily average combine efficiency of BIPVTW system was around three times of the efficiency of BIPVSF system.

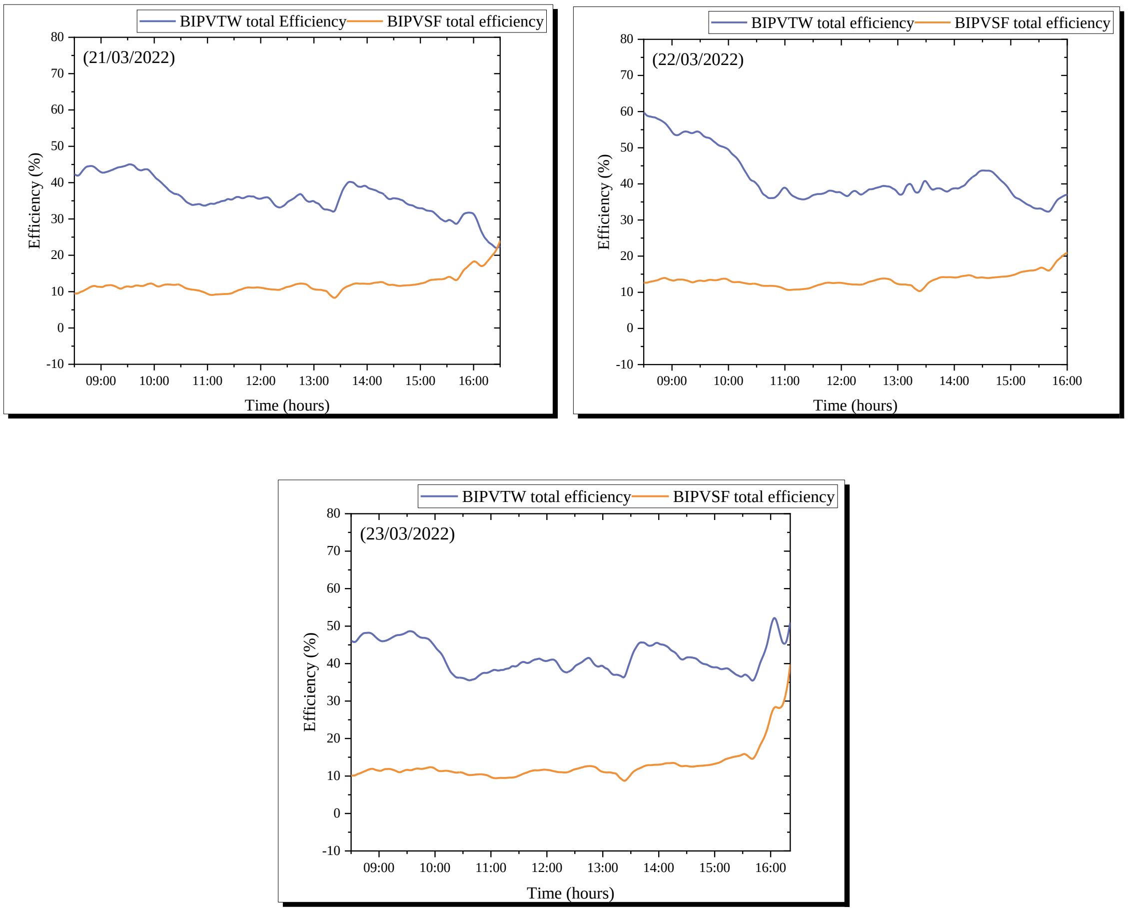

Figure 4-11. Daily instantaneous combine efficiencies of BIPVSF system and BIPVTW system.

Daily electrical power, thermal power and combine power produced by the BIPVSF system and BIPVTW system is shown in Figure 4-12 and Figure 4-13 respectively for all the three testing days. Total combine power of BIPVSF system on 21st to 23rd March is 63.5Wh, 85.9Wh and 66.7Wh sequentially while those of BIPVTW system are 176.3Wh, 234.8Wh and 199Wh. The total combine power produced by the BIPVTW system is 112.8Wh, 148.9Wh and 133Wh more than that produced by BIPVSF system on 21st to 23rd of March respectively.

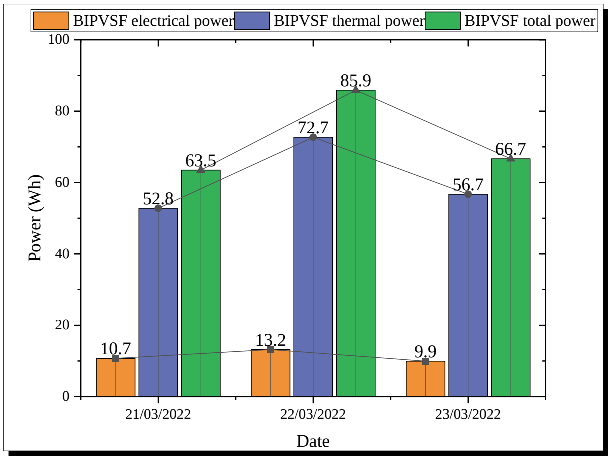

Figure 4-12. Daily BIPVSF system total electrical, thermal, and total combine power.

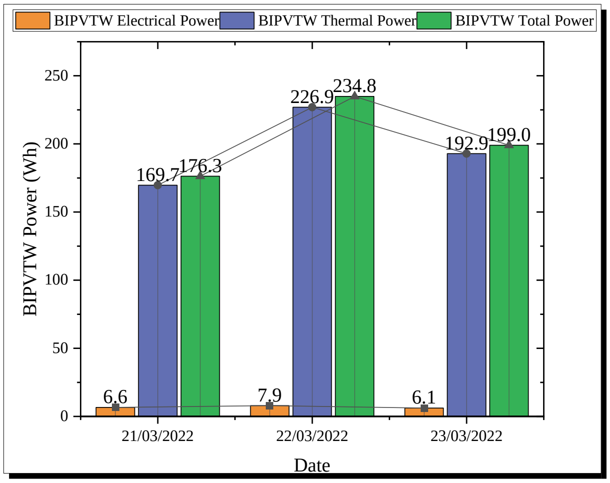

Figure 4-13. Daily BIPVTW system total electrical, thermal, and total combine power.

Summary

This chapter talk over the results obtained from the experimentation. The results are categorized into different subcategories as mentioned above. In initial section of the chapter temperature analysis of both systems was done and results were discussed. Then both recommended systems were analyzed based on their electrical performance and after that thermal performance of system was discussed. In last section, results of total combine (electrical and thermal) analysis of system were discussed.

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Chapter 5

Conclusions and Recommendations

5.1 Conclusions

The regions where there is high demand of space heating have high potential for BIPV systems. The area of research of this paper is the comprehensive photovoltaic and thermal usage of solar energy and energy conservation in buildings. This paper presents two different designs of BIPV walls system, one known as BIPVSF and second one is BIPVTW. Prototypes of both systems were prepared, and their individual electrical performance, thermal performance and combine (electrical and thermal) performance was observed using electrical and thermal data loggers. Polycrystalline solar PV modules were used for this study. The main results are as follow:

(1) The total daily electrical power generation of BIPVSF system were 10.7Wh, 13.2Wh and 9.9Wh on 21st, 22nd and 23rd of March while those of BIPVTW system were 6.6Wh, 7.9Wh and 6.1Wh. Daily electrical power generation of BIPVTW module was on average 38.9% less than that of the BIPVSF module. The maximum electrical efficiency of BIPVSF system and BIPVTW system was 6.02% and 3.96% respectively.

(2) The values of daily total heat gain of BIPVSF system were 190KJ, 261KJ and 204KJ on 21st, 22nd and 23rd of March respectively while the values of heat gain of BIPVTW system were 611KJ, 817KJ and 694KJ. Daily heat gain of BIPVTW system was on average 3.2 times of heat gain of BIPVSF. The results shows that daily average thermal efficiencies of BIPVSF system were 9.89%, 11.64% and 11.66 on 21st to 23rd of March, while those of BIPVTW system were 34.66%, 39.88% and 40.74%.

(3) Total combine power of BIPVSF system on 21st to 23rd March was 63.5Wh, 85.9Wh and 66.7Wh sequentially while those of BIPVTW system are 176.3Wh, 234.8Wh and 199Wh. Even though the daily electrical power output of the BIPVTW system for all the testing days was compromised up to 39% but the combine power produced by the BIPVTW system was 112.8Wh, 148.9Wh and 133Wh more than that produced by BIPVSF system on 21st to 23rd of March respectively.

(4) By using polycrystalline silicon module, the daily average combine efficiencies of BIPVSF system were 12%, 13.9% and 13.6% on 21st, 22nd and 23rd of March while those of BIPVTW system were 35.9%, 41.2% and 41.9%.

5.2 Future Recommendations

This study presents a hybrid solar building integrated Photovoltaic thermal system using air as a medium of heat transfer from module to the room and polycrystalline silicon technology. Mainly, the scope of this study was the building integrated solar PV walls, and the recommended designs are for those regions where heating load is a basic requirement of buildings. BIPV/T technologies are still struggling with poor electrical performance. The current achieve electrical efficiency can be enhanced by considering different parameters like the designing walls with optimized tilt angle of module, by using different materials or fluids as a source of heat transfer from module which can transfer heat in a very efficient way and reduce the temperature of module, and by using latest technology module with greater electrical efficiency. Furthermore, the thermal efficiency can be enhanced with the help of concentrating technology, enhancing the thermal insulation of system, and using some more efficient ways of heat transfer. Active heating can also be done to improve the combine efficiency of the systems.

Appendix: Publications

Experimental study on the performance of BIPV south façade and BIPV Trombe wall system.

Muhammad Siddique [a], Nadia Shahzad [a], Shayan Umar [a], Adeel Waqas [a], Sehar Shakir [a], Abdul Kashif Janjua [b, c]

[a] U.S-Pakistan Center for Advanced Studies in Energy (USPCAS-E), National University of Sciences & Technology (NUST), H-12 Campus, Islamabad, Pakistan

ABSTRACT

Building integrated photovoltaics (BIPV) technology can lead the world to establish sustainable buildings. Technically, this technology is struggling with low electrical power generation due to building structural limitations and elevated temperature, also performance of BIPV systems analyzed only based on their electrical output. Moreover, BIPV application as Trombe wall system significantly reduce the output power due to presence of glass in front of module. Thus, this paper presents an experimental study of two distinct BIPV wall systems and analyzed them based on their electrical, thermal and combine performance. Maximum electrical efficiency of BIPV south façade (BIPVSF) and BIPV Trombe wall (BIPVTW) was 6.02% and 3.96% respectively. The BIPVSF had a daily average thermal efficiency of 11%, whereas the BIPVTW achieved an efficiency of 38.52%. Furthermore, BIPVSF and BIPVTW systems respectively achieved daily average combine (electrical and thermal) efficiencies of 13.16% and 39.67%. The daily electrical power of BIPVSF system was 38.6% more than that of the BIPVTW but daily heat gain of BIPVTW system was 3.2 times of BIPVSF system. Despite the fact that the electrical power output is diminished when photovoltaics is used as BIPVSF and BIPVTW, the hybrid use of both systems can furnish a decent combined efficiency.

Key Words:

Solar photovoltaics, Sustainable Buildings, BIPV, Solar Façade, BIPVTW, PV/T.

Journal: Sustainable Energy Technologies and Assessments **Status:** Under Review