Integrated BIPV performance assessment for tropical regions: a case study for Bangalore

Gayathri Aaditya – Indian Institute of Science, Bangalore, India
Rohitkumar Pillai – Indian Institute of Science, Bangalore, India
Monto Mani – Indian Institute of Science, Bangalore, India

Abstract

Building Integrated Photovoltaic (BIPV) are Photo-voltaics (PVs) integrated as a building envelope. In addition to effectively generating energy, BIPV need to be energy efficient. They would need to passively regulate the responsiveness of the building envelope to the external environment to provide (natural) indoor thermal comfort, thus accomplishing the prime function of a building. Thermal comfort is an important parameter in building design as it contributes to overall health and productivity. Tropical regions, such as India, are generally characterized by high temperatures and humidity where passive designs need to integrate a combination of both, appropriate thermal massing and space orientation for adequate ventilation. BIPV poses unique considerations (and opportunities) as the inherent thermal mass is low and the radiative transmittance is high. Consequently, the BIPV also permits rapid heat-loss at night from the indoors through radiation, particularly when integrated as a roof. Regulating indoor thermal comfort in tropical regions poses a particular challenge under such conditions, as the Mean Radiant Temperature is likely to be high. Thermal comfort is also a key factor in assessing the energy efficiency of a building envelope as it determines the dependence on active (power-intensive) regulation for providing thermal comfort. Thus, building design strategies for optimizing BIPV performance would require an integrated consideration of three interdependencies, viz., maximizing PV performance, passive climate-responsive environment and natural thermal comfort. The paper investigates the performance of a 5.25 kWp roof integrated BIPV lab at the Indian Institute of Science, Bangalore (India) and is based on a year-long systematic study of parameters determining PV performance, indoor thermal comfort and building climate response. Regulating indoor thermal comfort is of particular concern as temperature stratification has been noted under BIPV roof. The current paper investigates the influence of thermal comfort on building climate response and BIPV performance and suitable strategies have also been evaluated through a simulation model.

1. Introduction

Building Integrated Photovoltaic Systems (BIPV) represent a recent trend in building design where PV forms the part of the building structure and fabric. These modules can be utilized as roof, facade, walls, glass, sunscreen or sunshade. In addition to other functional (building) requirements, BIPV also harnesses (and generates) energy. The electrical output from a photovoltaic system follows the solar radiation trend thereby generating maximum power during the peak sunshine hours. Tropical regions are characterized by high annual solar insolation making them ideal for any photo-voltaic application. However, two major challenges, electrical and thermal, pertaining to the application of BIPV in tropical regions stem out upfront. Firstly, the cell temperatures (in the tropical region) increase phenomenally compared to the ambient temperature resulting in a power loss. Secondly, integrating solar panels into the building thereby transmits a lot of heat to the interiors raising the issue of thermal comfort of the occupants. An appropriate solution is to design a BIPV structure, which can resolve the above mentioned problems by regulating its own heat gain to provide comfort.

PV as an envelope has unique opportunities and challenges in tropical regions in contrast to northern cold regions. The energy efficiency of PV is a key factor, as it determines the dependence on active (power-intensive) regulation for providing

thermal comfort. The roof is the most exposed to impacts of solar radiation, with low thermal mass, as it receives sunlight for practically the whole day, and in the tropics, the angle of incidence is close to the normal in the hotter parts of the day. Heat gain through the roof elevates ceiling surface temperature and causes radiant heat load on the occupants (Kabre, 2010) which also stratifies the air in the room.

This paper attempts to investigate, through experiments and building simulation, the thermal comfort in a BiPV structure installed at the Indian Institute of Science, Bangalore (tropical region, moderate climate) by identifying critical factors determining thermal comfort and provide solutions for attaining thermal comfort in BIPV structures through passive techniques.

2. Thermal comfort

Thermal comfort is an important aspect of buildings as it contributes to overall health and productivity. The standards such as ISO 7730 and ASHRAE 55-2004, define thermal comfort as subjective response and according to ASHRAE 55-2004 thermal comfort is defined as the "state of mind that expresses satisfaction with existing environment". There are many factors that influence the thermal comfort which can be broadly classified as environmental or physical factors (air temperature, humidity, air velocity and mean radiant temperature), physiological or personal factors (activity, clothing) and special factors (age, gender, asymmetrical radiation , draft, vertical temperatures, etc.). A single value integrating the various factors, which can assess the thermal environment, is called the thermal comfort index. Fanger's PMV - PPD model considers the major factors influencing thermal sensation. It has also defined the thermal comfort zones on the psychrometric chart by applying Fanger's laboratory based Predicted Mean Vote index (PMV) and Predicted Percentage Dissatisfied index (PPD) method. The results have been derived by controlling the three environmental variables viz., air velocity, mean radiant temperature and relative humidity and two personal variables viz., activity level and clothing insulation (Singh et.al., 2011) One of the important assumptions made by Fanger is that the mean radiant temperature is equal to the ambient temperature. The model rests in good agreement with HVAC buildings situated in cold temperatures. The limitation of this model, however, is that the PMV method overestimates the sensation of warmth than actual (Fanger, 2002). Many researchers have criticized the validity of PMV_PPD model for tropical countries. A study done by (Manikandan, 2011) elucidates that ASHRAE model is valid if the mean radiation inside the room is measured exactly then going by Fanger's assumption mean radiant temperature equal to ambient temperature. But many researchers have proved that the tendency to adapt to a changing external climate is the important factor for deciding thermal comfort. Because of the adaptability of the body to different climatic zones, the range of indoor temperatures in which humans feel thermally comfortable is highly dependent on the outdoor temperature. (Humpreys and Nicol, 1998). Figure 1, adapted from ASHRAE 55-2007, depicts the ranges of temperature for thermal comfort, in a non-air conditioned space, varying with the average outdoor temperature. Table 1 shows the acceptable operative temperature ranges for naturally conditioned spaces for Bangalore, India.

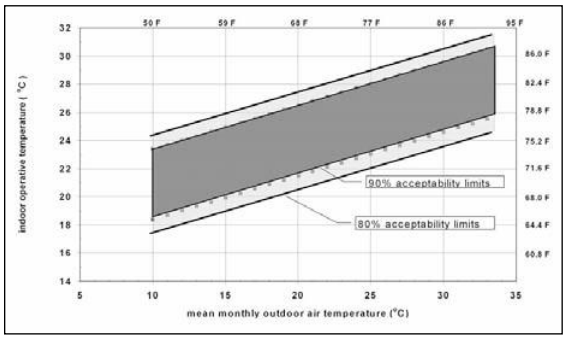

Fig. 1 – Acceptable operative temperature ranges for naturally conditioned space (Source: ASHRAE 55 - 2004)

3. Local thermal discomfort by ASHRAE standard 55-2004

It is necessary to understand and study the factors causing local thermal discomfort to determine

conditions for acceptable thermal comfort. These factors include draft, vertical air stratification, floor surface temperature and radiant temperature asymmetry. The acceptance criteria from all the local thermal discomfort factors must be met simultaneously in order to meet the thermal comfort requirements of the ASHRAE Standard 55-2004. The influence of these factors on the thermal comfort has been briefly discussed below.

Draft: Excessive air flow (or drafts) may result in an undesired body cooling. Sensitivity to drafts is greatest where the skin is not covered by clothing, especially the head region comprising the head, neck, and shoulders and the leg region comprising the ankles, feet, and legs. The requirements are based on sensitivity to drafts in the head region with airflow from behind and may be conservative for some locations on the body and for some directions of airflow. (ASHRAE 55-2004)

Vertical Air Temperature Difference: Thermal stratification that results in the air temperature at the head level being warmer than at the ankle level may cause thermal discomfort. The allowable difference between the air temperature at head level and the air temperature at ankle level is 3°C. Thermal stratification in the opposite direction is rare, is perceived more favourably by occupants, and is not addressed in this standard. (ASHRAE 55-2004)

	Maximum Temperature deg C	Minimum Temperature deg C	Average	**ASHRAE Naturally ventilated acceptable range**	
Jan	30.2	13.6	21.9	26.601	22.368
Feb	33.4	14.1	23.75	27.417	22.4955
Mar	34.8	12.9	23.85	27.774	22.1895
Apr	33.9	21.2	27.55	27.5445	24.306
May	40.6	13.1	26.85	29.253	22.2405
Jun	30.4	19.6	25	26.652	23.898
Jul	31	13.8	22.4	26.805	22.419
Aug	31.3	17.4	24.35	26.8815	23.337
Sep	33.4	14.3	23.85	27.417	22.5465
Oct	30.4	18.4	24.4	26.652	23.592
Nov	32.2	13.2	22.7	27.111	22.266
Dec	33	10.9	21.95	27.315	21.6795

Table 1 – Acceptable operative temperature ranges for naturally ventilated spaces in Bangalore

Floor Surface Temperature: Occupants may feel uncomfortable due to contact with floor surfaces that are too warm or too cool. The allowable range of the floor temperature is 19-29 °C. (ASHRAE 55-2004)

Radiant Temperature Asymmetry: The thermal radiation field about the body may be non-uniform either due to hot and cold surfaces surrounding the body and exposure to direct sunlight. This asymmetry may cause local discomfort and reduce the thermal acceptability of the space. In general, people are more sensitive to asymmetric radiation caused by a warm ceiling than that caused by hot and cold vertical surfaces. ASHRAE 55 states a condition on the maximum temperature difference from warm ceilings and suggests that it should be less the five degree centigrade, for obtaining the thermal comfort. (Christensen and Carr, 2012)

4. Case-Study: Building Integrated Photo-voltaic System at IISc

Bangalore lies in the south-east of the Indian state of Karnataka. It is positioned at 12.97°N 77.56°E, elevation of 1010 m .Winter temperatures rarely drop below 4°C, summer temperatures seldom exceed 30°C and it receives about 1300 mm of rain annually. The graph (figure 1) shows that for areas similar to Bangalore, thermal comfort will be

obtained if the operative temperature is between 21°C and 29°C. In the present analysis, an opaque type BIPV system installed on the roof (with no false ceiling or PV is not roof-mounted) of the experimental laboratory at the Centre for Sustainable Technologies (CST) of the Indian Institute of Science, Bangalore, India is considered. The lab is on the second floor of an existing load-bearing structure with one room measuring 18′2″ x 17′10″and the other measuring 14′11″x 17′10″. Stabilized Mud Blocks masonry has been adopted for the construction and is such that the south wall is not exposed to the sun. There are four windows in the experimental lab with an area of 14 square feet. The plan and section views of the BIPV lab are shown in Figure 2 and Figure 3. A photo-voltaic (PV) roof with a 15° slope true-south facing orientation for maximum solar gain is adopted. The mono crystalline silicon PV modules used are standard 150 W rated panels encapsulated in a toughened high transmittivity glass laminates. Rafters spanning a length of 6.3 m and a 0.2m depth fabricated from 2 mm galvanized iron sheets support these PV panels. A 0.2m air cavity below the PV panel permits effective extraction of warm air below the PVpanels. 35 panels run across the roof in a series-parallel combination to produce a desired maximum rated output of 5.25 kW_P at STC. The power generated is supplied to the grid directly through a grid-export conditioner equipped with an in-built inverter and a maximum power point tracker (MPPT). Daytime lighting in the rooms is taken care of by 10 glass panels symmetrically close to the edge of the roof, primarily to induce natural ventilation in the room below and also to extract hot air from below the panels. (Figure 4) The internal temperatures and humidity are measured using Suppco data loggers, which collect data at an interval of 5 minutes. The meteorological parameters have been monitored through a weather station appropriately installed on the BIPV lab. The weather station specification is provided in Table 2. Yearlong data is collected and analyzed to understand whether the temperatures inside are within the comfortable range (21 ° C -- 29 ° C). The internal temperatures were compared with ASHRAE specified comfort range values. The various discomfort factors are also assessed. The following sections deal with this appropriately.

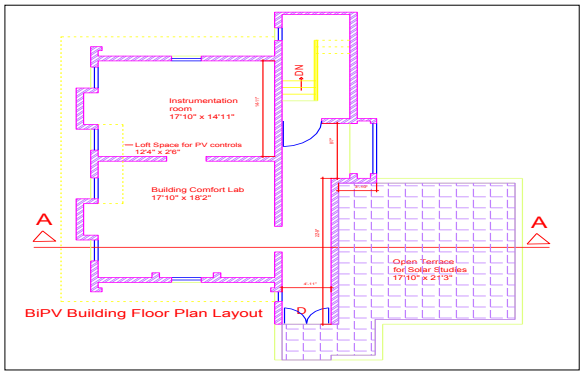

Fig. 2 – Plan of the BIPV Lab

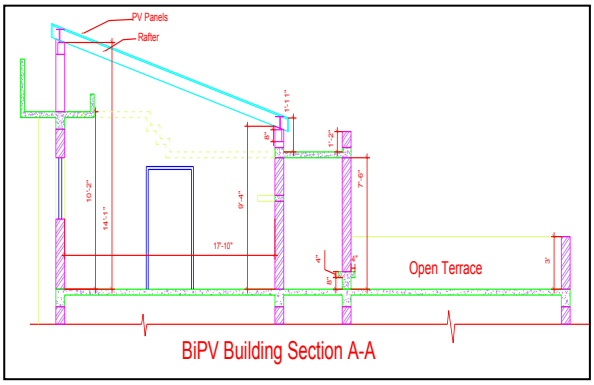

Fig. 3 – Section of BIPV lab

FFig. 4 – View of BIPV lab

Parameter	Measurement Range	Accuracy
Solar radiation	1-1250 W/m²	±5%
Temperature	-20° to 70° C	±0.6 ° C
Relative Humidity	0-100% (non-condensing)	±2%

Table 2 – Specifications of weather station installed at the BIPV roof, IISc

5. Results and Discussion

The various modes of heat transfer on a human being in the BIPV structure is shown in Figure 5. All modes of heat transfer play a role in maintaining the thermal comfort level of a human body. Temperature is considered to be the most important parameter influencing the thermal comfort index. Emphasis has been made to look at all possible temperatures to find out the discomfort factors.

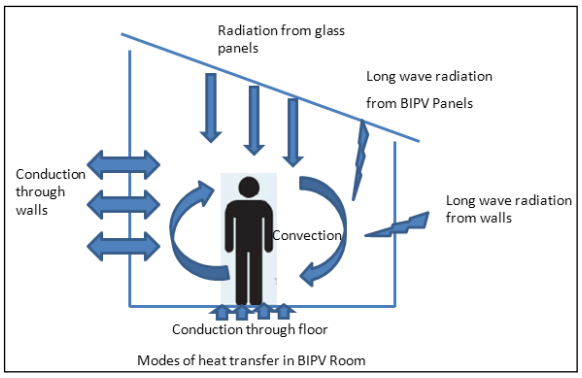

Fig. 5 – Heat exchange modes from the human body

Analyzing the temperature data (outdoor and indoor), the following observations are made.

1. The internal temperature of the BIPV structure is always higher than in a conventional building for eleven months. The figures below (Figure 9) show the comparison between internal and external temperatures for various months plotted for the different months in a year fortify the observation.

2. The maximum and minimum temperatures of every month are plotted the graph of ASHRAE STANDARD 55-2004 acceptable operative temperature ranges for naturally conditioned as shown in Figure 6. It was found that except for one month, the rest is not within the comfort zone. The data is further analysed to find out what period of the day is not comfortable. It was found that during the winter months the temperatures during the night time are lower than the comfortable range whereas in the summer months the temperatures during the day time are hotter and only in the month of August is it completely in the comfortable range (Table 3).

3. The Radiant Temperature Asymmetry is high as the ceiling temperatures are high. Due to the low thermal mass of PV, the temperatures of the PV reach 60 -70°C. The inside panel temperature and the air temperature at different levels is shown in Figure 7 where the temperature T1 is near the roof and T8 is near the ground. (Cena and Clark, 1981) have compiled the studies done by Griffiths and McIntyre 1974, Berglund and Fobelets 1987 and found that exposure to heated panels above the subject produced a greater level of dissatisfaction than for cooled ceilings and walls or heated walls (Hodder and Parsons, 2008). It can be readily realized that due to the nature of the roofing material used, the thermal comfort environment within the BIPV Structure are most susceptible to changes of the local weather conditions and is the reason for thermal discomfort in the BIPV structure.

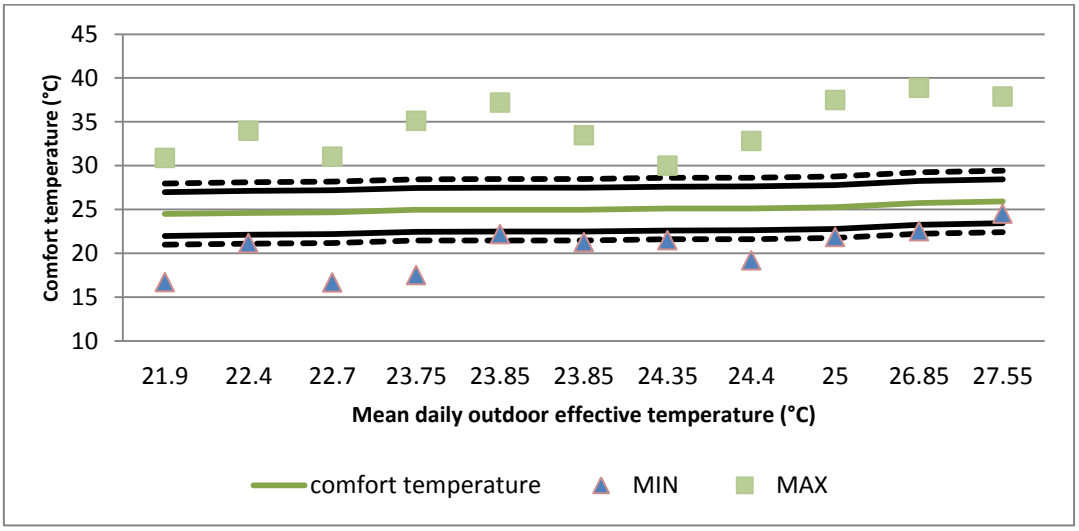

Fig. 6 – Minimum and maximum monthly temperatures on ASHRAE's acceptable operative temperature ranges

Month	Uncomfortable period	Time of the day when it is **Cold**	Time of the day when it is **Hot**	Minimum Temp. deg C	Maximum Temp. deg C
January	Day and Night	1 am to 9 am	--	16.7	30.87
February	Day and Night	1 am to 8 am	11am to 4 pm	17.5	35.1
March	Day and Night	--	11am to 6 pm	22.19	37.17
April	Day	--	10am to 7 pm	24.52	37.87
May	Day	--	11 am to 4 pm	22.51	38.85
June	Day	--	11pm to 6pm	21.86	37.48
July	Day	--	1pm -4 pm	21.15	33.96
August	Comfortable	Comfortable	Comfortable	21.48	30
September	Day	--	1pm to 3 pm	21.27	33.48
October	Day	--	1pm—3pm	19.2	32.82
November	Day and Night	4am -8am	1pm- 2pm	16.65	31.03

Table 3- Period during which the indoor temperatures are not within the comfortable range (for year 2012)

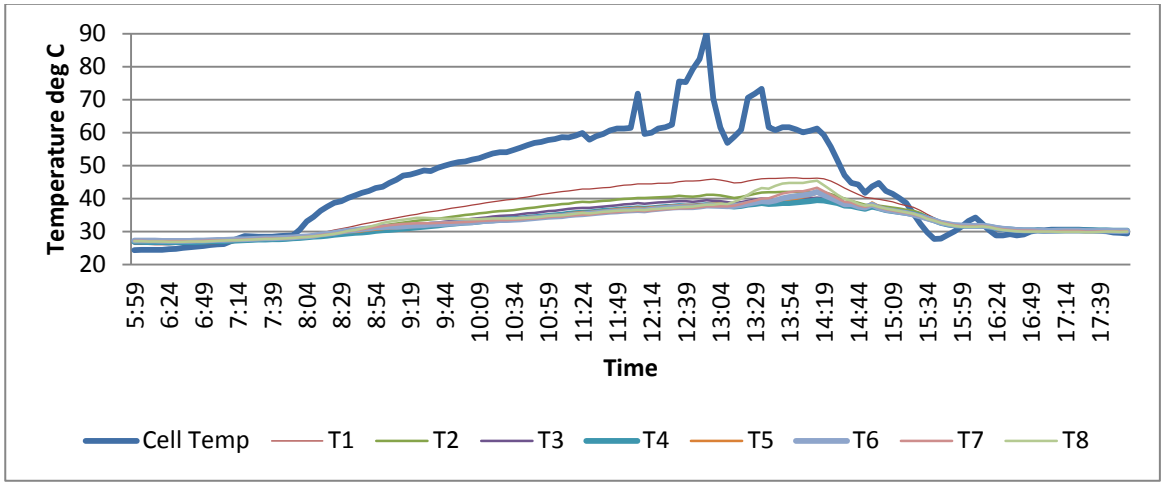

Fig. 7 – Air temperature at an interval of every 0.5m from the roof to the floor

6. Simulation

A computer-based building simulation model was developed in DesignBuilder (v 2.2.5), a CFD-based simulation package built over the successfully adopted EnergyPlus (Chowdhury et al and Wasilowski et al). Construction details, including general door window and heat gain from computer and inverter (power conditioning unit) etc., were given as input. The simulated temperatures were compared with the real-time monitored data for four months. Since the simulation model responds to climate files (statistical data) and the real-time thermal monitoring responds to actual climatic conditions, one cannot expect an exact one-to-one temperature correlation. The correlation is more than 0.85 for both indoor and outdoor temperatures. Figure 8 shows the comparison between internal and external temperatures for various months both measured and simulated. The model is tested with various strategies for summer by reducing the glass

panels on top (two panels) of the roof and in winter by placing a false ceiling in the room and removed the ventilators. Figure 9 shows that the reducing the glass panels helps in summer by reducing the temperature to 2-3° C, but in winter these strategies don't help as the temperature remains the same as shown in Figure 10.

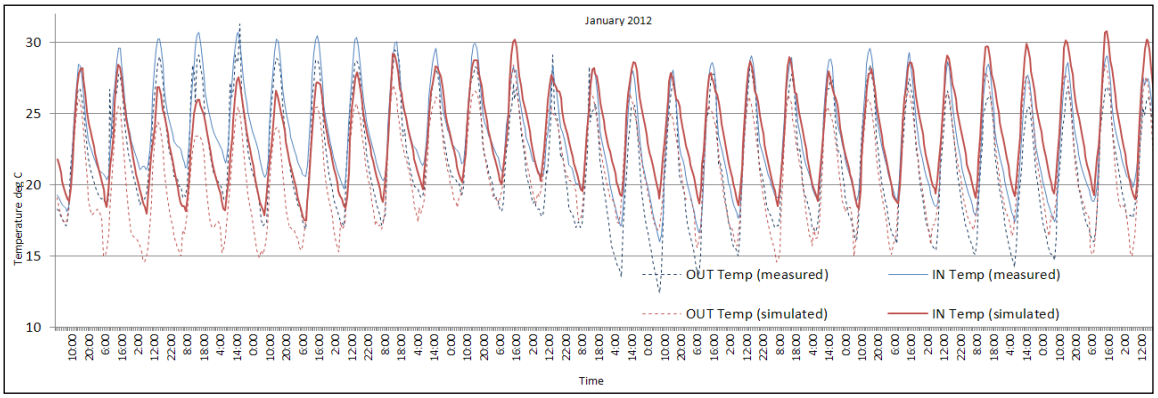

Fig. 8 – Comparison between internal and external temperatures for four months both measured and simulated (January 2012)

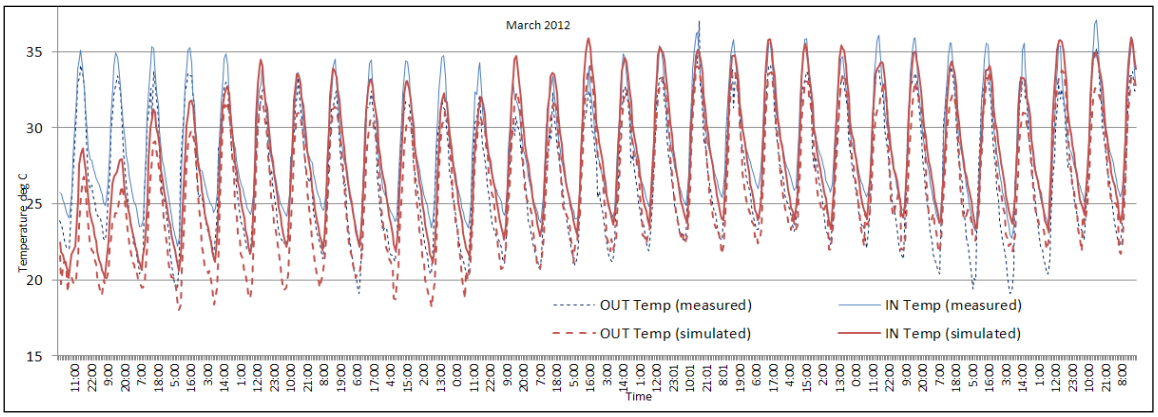

Fig. 9 – Comparison between internal and external temperatures for four months both measured and simulated (March 2012)

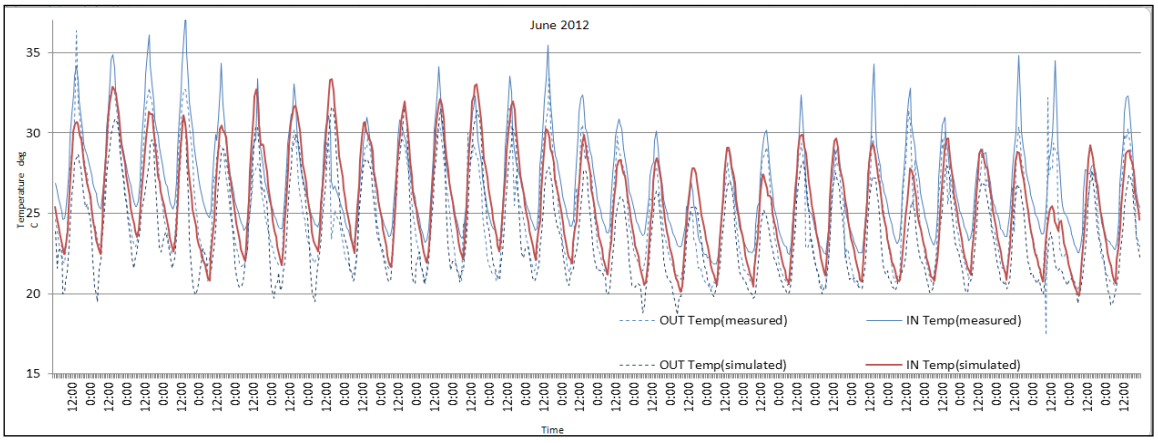

Fig. 10 – Comparison between internal and external temperatures for four months both measured and simulated (June 2012)

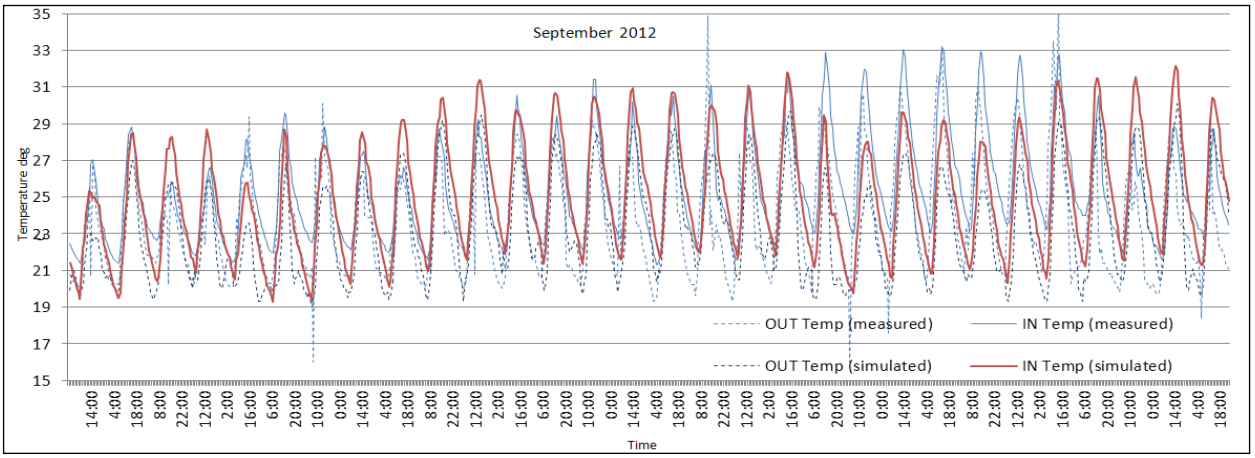

Fig. 11 – Comparison between internal and external temperatures for four months both measured and simulated (September 2012)

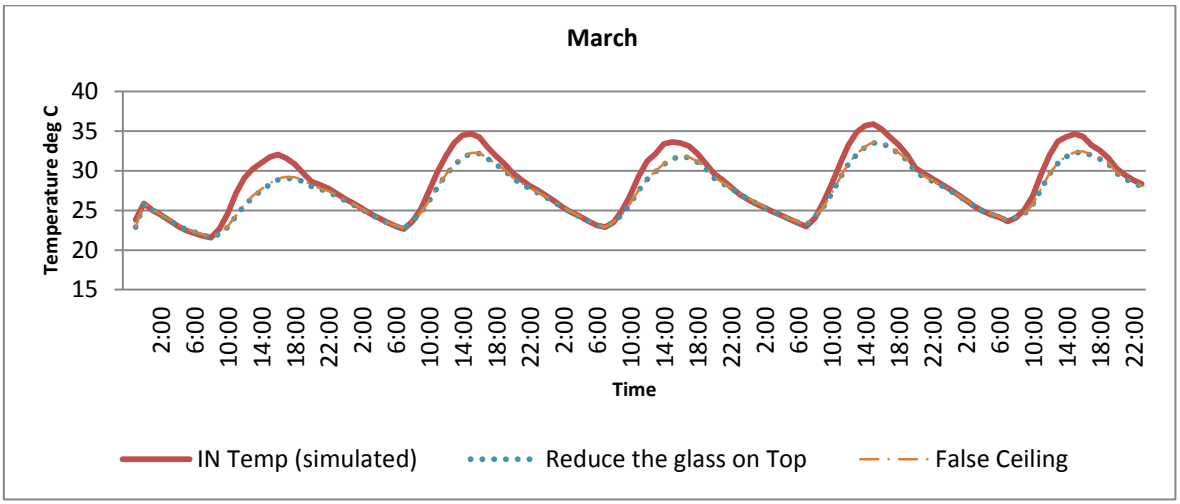

Fig. 12 – Simulated results of various strategies for summer months

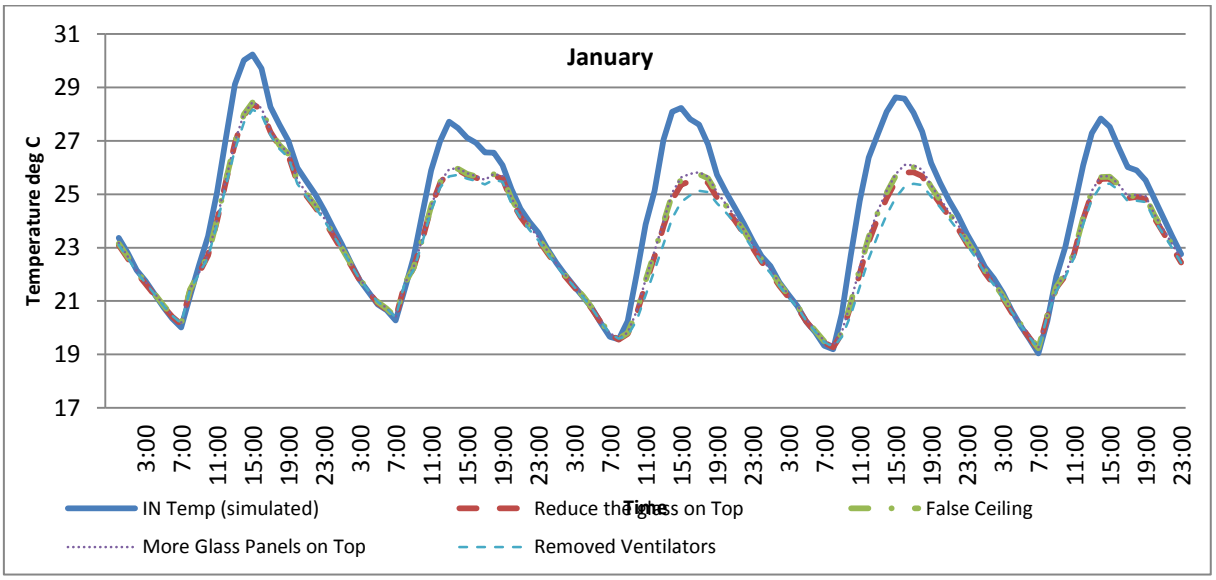

Fig. 13 – Simulated results of various strategies for winter months

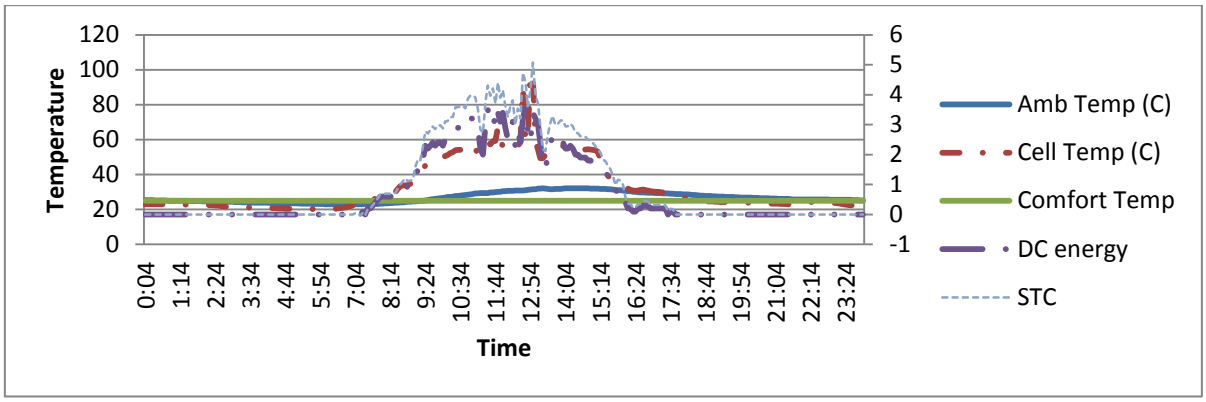

Fig. 14 – Comparison of electrical performance for regular and STC conditions and the thermal comfort temperature for a day in the month of September

7. Conclusion

1) Climatic-response in a BIPV structure depends on a complex correlation between PV performance and indoor thermal comfort.

2) In tropical regions, BIPV installations are required to tackle in design for the degrading effect of high PV (cell) temperatures and indoor radiant regimes (MRT); the former lowers energy generation efficiency and the latter causes indoor discomfort necessitating energy for maintaining thermal comfort particularly when the energy generation potential is the highest (Figure 11). The lower thermal mass of a PV building envelope permits a higher thermal transmittance and increases the indoor temperatures. With lower thermal mass, PV cell temperature is more sensitive to variations in solar insolation as compared to indoor temperature variations. Despite lower thermal mass, the radiation from the roof to the indoors offers consistent warming potential, which can be exploited in colder regions.

3) Solar passive designs for BIPV need to be considered to make BIPV structures thermally comfortable. However, completely neutral thermal comfort conditions may not be obtained in such a relatively uncontrolled environment because of the thermal mass of the PV and the nature of the construction at least the adaptable range should be obtained through passive strategies to reduce the temperature inside.

4) For the specific study various strategies are simulated that can provide opportunities to lower indoor temperatures during summer and to increase the night temperatures during winter to regulate thermal comfort. The strategies, which were simulated for summer, hold positive, whereas the strategies tested for winter do not serve the intended purpose. Hence other effective strategies need to be tried and tested.

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