Cell (Module) temperature regulated performance of a Building Integrated Photovoltaic system in tropical conditions

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Abstract

The performance of a building integrated photovoltaic system (BIPV) has to be commendable, not only on the electrical front but also on the thermal comfort front, thereby fulfilling the true responsibility of an energy providing shelter. Given the low thermal mass of BIPV systems, unintended and undesired outcomes of harnessing solar energy – such as heat gain into the building, especially in tropical regions – have to be adequately addressed. Cell (module) temperature is one critical factor that affects both the electrical and the thermal performance of such installations. The current paper discusses the impact of cell (module) temperature on both the electrical efficiency and thermal comfort by investigating the holistic performance of one such system (5.25 kW_p) installed at the Centre for Sustainable Technologies in the Indian Institute of Science, Bangalore. Some recommendations (passive techniques) for improving the performance and making BIPV structures thermally comfortable have been listed out.

Key words: BIPV, cell (module) temperature, energy efficiency, thermal comfort, tropical regions.

1.0. Introduction

Building integrated photovoltaic (BIPV) systems are slowly gaining recognition as a novel means of harnessing solar energy. As the name suggests, BIPV systems are components of a building in the form of a building envelope such as roof, façade, shading device or architectural accessory. When PV is added to the existing envelope it is called as Building Applied PV (BAPV). As sustainable power generators, they tend to reduce the overall greenhouse gas emissions. BIPV systems can be easily adapted on both new and existing buildings, and thereby save up on land requirements. According to a recent BCC Research report [1], BIPV make up a small but noticeable part of the world PV market; BIPV roofing is considered to be one of the largest market segments with a compound annual growth rate

of 51%. Most regions in India receive good solar insolation throughout the year. On an average, the country has 250 sunny days per year (also translates to 5000 trillion kWh per year) and receives an average hourly radiation of 200 MW/km². It is also estimated that around 12.5% of the land mass in India could be used for harnessing solar energy, which could be further increased by the use of building integrated PV [2].

Despite the advantages offered by BIPV, their widespread utilization is hindered by complex intertwined factors. To be an energy-efficient building envelope, the BIPV system would need to passively regulate its responsiveness to the external environment and also maximize the electrical yield. However, the requirements for climate-responsive building design may infringe upon those required for optimal PV performance [3]. The generation of electricity is by harnessing maximum solar energy – this depends on (a) unalterable factors: location (latitude, longitude and altitude) and type of climate, and (b) alterable factors: system configuration (solar exposure, slope, orientation and sizing), wind patterns, dust conditions and maintenance. A major issue of concern here is the efficiency of the solar PV array systems. Apart from the inherent material-related losses in the efficiency of commercially-available photovoltaic panels, there is further decline in efficiency in the working atmosphere mainly due to cell (module) temperature and dust settlement [4] on the modules (Figure 1).

Figure: 1. Losses during the conversion of solar insolation to electricity.

The temperature of a solar cell (module) in operation increases phenomenally (especially true in tropical regions), resulting in a decrease in the output. The working of a solar cell is based on the photoelectric effect wherein electrons are emitted from the surface of a material as a consequence of absorption of energy from short wavelength electromagnetic radiation. The current generated is directly dependant on the solar radiation and decreases as the temperature of the cell (module) increases. The voltage, however, is practically constant even at low solar radiation levels but drops with increasing temperatures. Thus, the current and voltage from a solar cell (module) have to be optimized for maximum output. Tropical regions are characterized by high ambient temperatures; the consequence of this is outlined in Figure 2. This rise in temperature in BIPV systems, which have low thermal mass, may result in thermal discomfort of the occupants and also increase the cooling load of the dwelling. It is, therefore, necessary to optimize both the electrical and the thermal comfort-related

performance of BIPV systems to make them attractive energy solutions. Here, temperature is the quintessential and common factor determining the effectiveness of these structures. Most of the temperature based studies have been carried out on the basis of simulations and have dealt with the performance issues of BIPV [5], [6], [7], [8] and [12]. This current study is a real-time experimental investigation with a holistic and unique approach through electrical and thermal comfort performance of the BIPV system.

Figure: 2. Consequences on BIPV performance due to high ambient temperatures.

A study was carried out on the overall performance of a 5.25 kW_p BIPV system installed at the Center for Sustainable Technologies (CST) in the Indian Institute of Science, Bangalore with a focus on the consequence of cell (module) temperature regulation. Since a cell (module) temperature is difficult to be measured the temperature of the back-side of a PV panel is measured in this study. Module (back-side) temperature is not equivalent to the cell temperature; however, the maximum error due to this measurement is around 5 deg C under-estimation as suggested in [9]. The range of temperature is more important in this study compared to the accuracy of it, module temperature is loosely considered as the cell temperature. The observations along with some strategies to reduce the cell (module) temperature (and eventually improve performance) are discussed in this paper.

2.0. BIPV system under study

The BIPV system (Figure 3) is installed as the roof (with no false ceiling, in the second floor) of the experimental laboratory at CST (12° 58'N, 77° 38'E, 921m above MSL). The specifications for the building and the PV system are given in Tables 1, 2 and 3. The authors have given a detailed description of the same case in a recent publication [10].

Table: 1. Building specifications.

* See Table 2.

Table: 2. BIPV system specifications.

Table: 3. PV panel specifications

Figure: 3. BIPV system as roof.

3.0 Appraisal of the installed system

The performance of the BIPV system – electrical and thermal comfort-related – has been studied based on data collected from May 2011–April 2012. A summary of the electrical performance [5] and details of thermal comfort-related performance are presented.

3.1. Performance: Electrical

For a critical assessment of the system, the efficiency, performance ratio and losses were calculated. Data related to the power generated (both AC and DC) were retrieved from the grid export conditioner. A cumulative energy of ~ 4000 units was supplied to the grid during the study period. It was observed that the system output increases during months of good solar insolation even though efficiencies are low.

3.1.1. Efficiency

Efficiency is the fraction of solar energy falling on the panels that is converted into electricity. The system efficiency is considered as the ratio of final AC energy to the solar energy falling on the surface for the given time period. The installed system has an average efficiency of 6%. An interesting observation is that the maximum efficiency is in January while the maximum output is in March; this may be due to the higher cell (module) temperature. For mono-crystalline silicon panels, the best operating conditions would be high insolation levels with low cell (module) temperatures.

3.1.2. Performance ratio

This is the ratio of the useful energy to the energy that would be generated by a lossless ideal PV plant with solar cell (module) temperature at 25°C and identical insolation levels. It is noted that the monthly performance ratio is maximum in winter (with low cell (module) temperatures), following the same trend as the array efficiency. An average performance ratio of 0.5 was observed.

3.1.3. Losses

Losses pertain to capture and system losses. System losses are dependent on inverter efficiency (ratio of AC to DC power generated – 91% in this case) and are constant. Capture losses depend on solar insolation and are found to increase with a rise in cell (module)

temperature. Figure 4 summarises the electrical performance of the BIPV system during the study period.

Figure: 4. Efficiency, performance ratio and losses.

Though cell (module) temperature is a critical factor that affects performance, the efficiency of the system is dependent on many other factors (as illustrated in Figure 5) [5]. An understanding of the significance of each parameter is essential.

Figure: 5. Salient factors affecting system efficiency.

3.2. Performance: Thermal comfort

Thermal comfort is an important aspect in buildings as it contributes to overall health and productivity. According to ASHRAE 55-2004 [11], thermal comfort is the ‘state of mind that expresses satisfaction with existing environment’. This standard provides the acceptable range of operative temperatures for naturally ventilated spaces in Bangalore (Table 4); the thermally comfortable range is between 21°C and 29°C.

Table: 4. Acceptable range of operative temperatures for naturally conditioned spaces in Bangalore.

For an appraisal of the BIPV system in terms of thermal comfort, internal parameters such as indoor temperature, humidity, air velocity and mean radiant temperature were measured. This was done using calibrated LTH-Suppcoco data loggers and a thermal comfort meter set up in the experimental laboratory; data was collected at 5 minute intervals. External data, that is, the meteorological parameters were monitored through a weather station appropriately installed near the BIPV structure. Some interesting observations were made by analysing this data:

1. The internal temperature in the BIPV structure is higher than the ambient outdoor temperature throughout the year (Figure 6).

Figure: 6. Comparison of internal and external temperatures of four months (for a typical day).

2. The maximum and minimum indoor temperatures for each month during the study period were plotted on a graph [12] (Figure 7) with reference to ASHRAE’s [11] acceptable

operative temperature ranges (see Table 4). It was found that except for one month, the temperatures do not lie within the comfort zone.

Figure: 7. Minimum and maximum monthly temperatures on ASHRAE's acceptable operative temperature ranges.

3. The radiant temperature asymmetry is high as the ceiling temperature is high than the floor temperature. Due to the low thermal mass of BIPV, the temperature of the cell (module) reaches 60–70°C. The temperature of the lower surface of the panel and the air temperature at different levels (1 m intervals) inside the room are shown in Figure 8; here T1 is the temperature near the ceiling and T4 is near the ground. It is immediately realized that this trend mimics that of the solar radiation, thus proving that silicon panels have a very low thermal mass and transmit most of the radiation inside the room; this causes high ceiling temperatures which is the cause for asymmetric thermal radiation leading to thermal discomfort.

Figure: 8. Cell (module) temperature versus air temperature (°C) at different levels (1 m intervals from ceiling)

The temperature inside the BIPV structure being uncomfortable can be attributed to the roofing with low thermal mass and the high cell (module) temperatures which reach upto 60°C. Thermal comfort within the room are susceptible to changes in local weather conditions; in tropical regions, this is undesirable and uncomfortable.

3.3. Comparison of electrical and thermal comfort-related performance

A comparison between the electrical and thermal comfort-related performance of the BIPV roof is depicted in Figures 9 and 10 [12]. They clearly show that cell (module) temperature is the cause of the performance drop in both cases. Pertaining to the effects of cell (module) temperature, it is advisable to adopt strategies to utilize the heat from the panels or even prevent heat generation. The following sections deal with these strategies.

Figure: 9. Comparison of performance: electrical (under regular and standard test conditions (STC)) and thermal comfort-related – on a day in April 2012.

Figure: 10. Comparison of performance: electrical (under regular and standard test conditions (STC)) and thermal comfort-related – on a day in September 2012.

4.0. Passive cooling and water cleaning

The BIPV system studied is rated at 5.25 kW and supplies around 3.9 kW of power to the grid at peak hours. The manufacturers have rated the efficiency of a single panel at ~11.29 % but the system efficiency is only ~ 6%. The efficiency of a photovoltaic system follows the trend of the open circuit voltage at higher cell (module) temperatures. The increase in the short circuit current due to higher temperatures is very low compared to the decrease in the open circuit voltage at the same temperature. It is therefore essential to have a tracking and a cooling mechanism in order to maximize power. For a BIPV roof, tracking becomes difficult and a cooling mechanism means an increase in operational costs.

In the present scenario, passive cooling was provided to the roof. This was done by maintaining an air gap of 203 mm below the panels. Since there is a slope to the roof, this air gap automatically enhances natural convection at the bottom and creates air drafts which help in reducing the temperature. Also, water cleaning was carried out consistently every alternate day as part of the cleaning cycle. This was done by pouring water on the panels for a time span of 10 minutes and then mopping with a cloth; it consumes ~ 40 litres of fresh water. Dust and dirt accumulate on the panel surface despite regular cleaning, which is a tedious mechanical process carried out during peak hours of sunshine especially at noon. Although the prescribed norms suggest that cleaning of the panels should be carried out early in the morning or late in the evening to avoid shadowing, it was carried out during peak hours in this case to understand the impact of lowering the temperature. To study this, the time span of pouring water was increased by another 20 minutes. A sudden rise in efficiency was observed as shown in the graphs below (Figure 11). It was also seen that this rise in efficiency is not sustained and falls after the cleaning is over. It can thus be inferred that this peaking in efficiency is due to the drop in the solar cell (module) temperature. However due to such sudden drop in temperatures thermal stresses may be induced. Further investigation is required [13].

Figure: 11. Effect of water cleaning on efficiency.

5.0. Strategies to increase efficiency by reducing cell (module) temperature

Building integrated photovoltaic systems can be used in residential, commercial, industrial, government and public sector undertaking buildings. For the penetration of BIPV technology – which has a high initial cost, low efficiency and low thermal mass – into the society, it is essential to increase the efficiency and the thermal comfort it provides. This has to be done through cost-effective strategies that can reduce the cell (module) temperature. If the heat generated can be utilized to heat the interior, it would be useful; but this is not that important in tropical regions as in cold places.

The strategies can be broadly categorized into two: one is cooling beneath the panels and other is cooling above the panels (see Figure 12).

Figure: 12. Categorization of the various strategies to cool PV panels.

Realizing the impact of water cooling in the above section, some strategies utilizing water cooling alone are discussed below. These are ideas that have to be tested to prove their viability. They may be considered worth researching and exploring.

- **Water tanks:** The tanks in buildings are generally deep depending on the water requirements. These can be built shallow but spread throughout the roof. This design will help keep the panels cool while storing water, without any extra investment.
- **Coupled hybrid systems:** Attaching a solar still or air heating system that will utilize the heat lost from the PV system improves the entire system efficiency. Another possibility is to make the module entirely transparent with the bottom resting on copper tubes (painted matt black) carrying water or any other liquid, thus utilizing the heat and maintaining the cell (module) temperature.
- **Sprinkler systems:** Such systems can be utilized for frugal use of water in regulating the cell (module) temperature and as a cleaning mechanism for dust and dirt. The costs incurred should be balanced with the extra power generated. It could be a timed sprinkling throughout the day or a continuous stream-flow of water on the panels during the peak solar insolation period.

- **Design changes:** On top of the PV module, two high-transmittance glasses can be used with an air gap between them. Air would act as an insulator, thus controlling the heating-up of the panels. A modification can be made to the above idea: instead of the special cover glass, a normal high-transmittance glass can be utilized and instead of the air gap, a layer of water can be maintained. Water not only acts as an IR inhibitor but also has a very high specific heat capacity; this prevents it from heating up soon and thus regulates the cell (module) temperature.
- **Roof ponds:** Water stored on the BIPV roof acts as a heat source and heat sink during winter and summer respectively. During summer days water (with high thermal capacity) keeps the solar heat away, thereby keeping the BIPV panels cool and increasing the efficiency. During nights and winters and depending upon the climate, the water ponds can be covered to reduce heat losses (see Figure 13).

Figure: 13. Panel cooling techniques (water based) above the BIPV roof.

6.0. Conclusion

Building integrated photovoltaic systems hold tremendous potential to cater to the needs of a building, especially residential. The present analysis reveals that ample amounts of electricity (by increasing the efficiency) can be generated by bringing down the cell (module) temperature. This also makes room temperatures to be thermally comfortable. Design considerations to maximize electrical performance alone may not be desirable. Efforts to improve the thermal comfort of the occupants in a natural way should also be looked upon; otherwise, this would raise the cooling loads of buildings in tropical regions. In this regard, some strategies based on water cooling have been looked at – they try to keep the solar panels cool, thereby increasing the efficiency and the thermal comfort inside the room. They need to be further researched upon.

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Table: 1. Building specifications.

S. No.	Building element	Materials	Specification	Remarks
1	Walls	Stabilized mud block masonry	7% cement +(30% Clay +15% Silt+55% Sand) by weight	High thermal mass
2	Roof	PV *	Sloped @15° and oriented south	For maximum annual solar heat gain and easy drainage of water
3	Ventilator	Natural	0.20 m air cavity	Removal of hot air
4	Skylight	Glass	10 panels spread across the roof	Illumination

* See Table 2.

Table: 2. BIPV system specifications.

PV system details	5.25 kWp under standard test conditions	<p>Aluminium Frame</p> <p>High Transmission toughened glass</p> <p>Ethylene Vinyl Acetate (EVA)</p> <p>Mono-crystalline Silicon Cells</p> <p>EVA</p> <p>Tedlar</p> <p>Cross section of the PV Module</p>
Type of PV	150 watts peak (Wp) mono-crystalline silicon	
Rated efficiency	11.9%	
Area covered	44.8 m ²	
No. of panels	35	
Type of system	Grid connected	
Inverter	Gridexport conditioner with Maximum Power Point Tracker.	

Table: 3. PV panel specifications

Parameter	Description
Peak Power (W)	150
V_{OC} (V)	42
I_{SC} (A)	4.8
V_{MAX} (V)	35
Cell Efficiency (%)	13.5
Module Efficiency (%)	11.9
Temperature Coefficient of Power (%/deg C)	0.45

Table: 4. Acceptable range of operative temperatures for naturally conditioned spaces in Bangalore.

	Temperature (°C)		
	Maximum	Minimum	Average
January	30.2	13.6	26.601
February	33.4	14.1	27.417
March	34.8	12.9	27.774
April	33.9	21.2	27.5445
May	40.6	13.1	29.253
June	30.4	19.6	26.652
July	31	13.8	26.805
August	31.3	17.4	26.8815
September	33.4	14.3	27.417
October	30.4	18.4	26.652
November	32.2	13.2	27.111
December	33	10.9	27.315