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Performance comparison of BAPV and BIPV systems with c-Si, CIS and CdTe photovoltaic technologies under tropical weather conditions

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ABSTRACT

This paper compares the performance of photovoltaics (PV) for building applications in two configurations: building applied photovoltaics (BAPV) and building integrated photovoltaics (BIPV). A 32.7 kWp PV capacity is proposed for a roof building and its performance in BAPV and BIPV configurations with three PV technologies namely crystalline (c-Si), CIS, and CdTe is analyzed. The standard methodology with performance parameters such as energy yield (EY), yield factor (YF), capacity utilization factor (CUF), performance ratio (PR), and losses is used. It is found that the EY, YF, and year to year energy production variability of BIPV and BAPV technologies varies from 43,700–46,800 kW h, 1336.39–1431.19 kW h/kWp, and 1910–2100 kW h respectively. The CUF and PR vary from 15.25–16.33%, and 72.23–77.36% respectively. Irrespective of PV configuration and technology, observed losses due to the angle of incidence, spectral effects, effects of change in irradiance and module temperatures are observed to be − 2.8%, − 1 to − 5%, and − 7.4 to − 13.6% respectively. Total system losses range from − 22.6 to 27.8% causing a fair amount of loss in the PV efficiency. Among, three PV technologies, CdTe is observed to perform better than CIS, and c-Si.

1. Introduction

Among the available renewable energy technologies, solar photovoltaics is considered to be the most promising one due to its advantages in energy generation, operation, and maintenance. Solar photovoltaics is one of the simplest energy conversion devices for the efficient use of the sun's power into useful energy. In recent years, the use of solar photovoltaics for urban buildings has become more popular. This application of PV, transforms the existing building into energy producer from energy consumer [1]. In this application, photovoltaic modules are integrated or attached to the building during the construction or after the construction phase. Here the most efficient and quality construction is to be adopted with appropriate materials [2]. Solar PV panels will become the exterior construction materials for buildings. This serves as a protective shield for the buildings from any weather changes, noise, smoke, etc. Also acts as the thermal insulating material for the buildings. With few other transparent or semitransparent technologies of solar photovoltaics, BIPV serves as energy savers by providing enough daylight and illumination into the buildings indoors [3]. The PV application in buildings is gaining much popularity due to the lack of enough ground area. The actual dead load of the building,

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i.e., walls, rooftops made with concrete are reduced or replaced by a flexible transparent or semi-transparent PV module technologies [4–6]. The use of PV technology to replace building construction materials reduces the cost of construction [7,8]. However, to have an efficient BIPV or BAPV system, one should consider the factors that influence the performance; these factors include solar radiation, PV technology, PV module temperature, installation angle, tilt angle and orientation, azimuth angle, shading conditions, and spectral effects, etc. [9]. The significant factors that influence the efficient BIPV/BAPV installation are design optimization, PV materials with fewer losses, efficiency, optimal arrangement (either roof or façade), cost of the system, operation and maintenance. However, most of the studies were limited to the fields like BIPV materials and advancements [9], BIPV modules for various BIPV projects [10], transparent and semitransparent PV materials [4–6], BIPV barriers and challenges [11]. Also, the design and economic analysis of BIPV and BAPV are more important [12–17]. For the practical implementation of BIPV systems, prior information on its energy performance will be very much useful for planning and development. The performance is highly uncertain due to the nature of incident solar radiation on the PV panels, temperature, and shading conditions as per the location which causes a negative impact on the performance yields. These impacts will have a direct effect on the energy generation and cause a decrease in power output in BIPV system than expected. Another important aspect is to identify the best PV technology for buildings to enhance the final energy yield. Hence, to understand the feasibility of BIPV or BAPV systems for a geographical location (solar radiation and other weather conditions will vary for a location to location), performance studies must be carried out. The objective of the study are as follows:

- To investigate the applicability of solar photovoltaic systems for building applications in two possible configurations BAPV and BIPV and to compare and analyze the performance of BIPV and BAPV for tropical climatic conditions in Malaysia considering the various losses in the system.
- To identify the suitable PV technology among c-Si, CIS, CdTe for building applications in Malaysia.

2. Description of BAPV and BIPV systems

Buildings which can produce power with the help of solar can be referred to photovoltaic power stations. Solar photovoltaic panels are integrated or attached to the roof or façade of the building to generate electrical power. Based on the method of installation and construction in the building, the PV system is classified into two systems: building applied photovoltaics (BAPV) and building integrated photovoltaics (BIPV). In BAPV, the PV modules are directly attached to the buildings using additional mounting structure and moving rails [10]. Here, the PV modules do not have any direct effect on the building structures and the way they function. The PV modules are installed at certain tilt angles either on roof or façade (BAPV-wall, BAPV sloped roof) based on local weather conditions. BAPV can also be installed on the horizontal roof and vertical wall [15–17]. In BIPV, the PV modules are integrated within the building structures mainly into roof or façade. Such integrations can also be referred to as BIPV facades and BIPV-roof [8]. Here the PV modules will replace the traditional building materials used for the construction of roof or walls by the BIPV products. This includes the PV modules in the form of transparent or semitransparent glass [4–6]. The BIPV is installed considering the local weather conditions and the building architecture [9]. In this case, the BIPV system will have some impact on the building structures and their functionality. Even though both BAPV and BIPV systems falls under building applications of photovoltaic systems, there are few major differences regarding their construction and installation procedures. It is quite difficult to categories a PV system in building application whether it is BAPV or BIPV unless until the mounting method and installation are specified explicitly. Hence a comparison is necessary, and few differences are highlighted in Table 1 [18]. However, the electrical configuration is similar for both, and their schematic view is shown in Fig. 1. BIPV or BAPV systems generate electricity which is relatively free from greenhouse gas emission during the operational phase with no ground or land space requirements. Hence the adoption of PV technologies for buildings either in the form of BAPV or/and BIPV is highly advisable.

3. Performance evaluation of BAPV and BIPV

3.1. Study location

Malaysia is a country that experiences a tropical climate with excellent potential for solar energy. Study location where the BAPV or/and BIPV systems are proposed is Universiti Malaysia Pahang (UMP). The university is in the Pekan region of Malaysia which experiences tropical weathers. The site is completely exposed to better sunshine throughout the year. The building selected for the study is having a roof area that can accommodate PV. The photovoltaic modules are planned to incorporate into the building in two configurations: BAPV and BIPV. The capacity of the proposed system is estimated to as 32.7 kWp and it is based on the available roof

Table 1
BIPV and BAPV Comparison [18].

Building integrated photovoltaics	Building applied photovoltaics
Integrated directly within the building structures like roof or facade	Indirect integration by using mounting hardware and roof perforations
Lightweight, and heavyweight	Heavyweight
Durable	Breakable
Highly resistance to winds	Lift or drag is possible
Aesthetically pleasing	Clunky looking

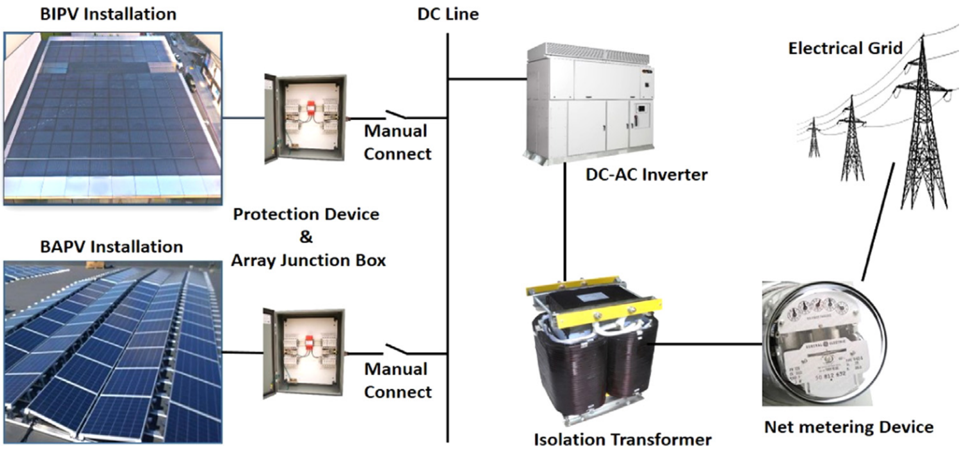

Fig. 1. Schematic view of grid-connected BIPV and BAPV system.

area.

3.2. Modelling of BAPV and BIPV systems

For analyzing the feasibility of BAPV and BIPV, one should first consider the various factors that are going to affect the system performance. The location and weather parameters where BAPV and BIPV are proposed are to be studied clearly. After site selection and weather parameter study, a simulation methodology is applied by selecting appropriate simulation tool. The proposed 32.7 kWp BAPV and BIPV systems were simulated using the photovoltaic geographical information system (PVGIS) [19–23], the specification required for carrying out the simulation are given Table 2.

PVGIS is one of the well-known software tools developed by the European Commission. It allows the users to analyze the performance of stand-alone, grid-connected, and tracking photovoltaic systems for various locations in various installation configurations over the regions of Europe, Africa, and Asia. This tool has high-resolution solar maps related to accessible locations. From this map, one can understand the variations of solar irradiation over the horizontal surface, an inclined surface or at an optimally inclined surface also. Apart from the maps, it also provides the database related to solar irradiation on an average daily, monthly, and hourly irradiance from the year of 2007–2016 respectively. It also provides the irradiation in the form of TMY files in three different databases ranging from 2005 to 2014, 2006–2015, and 2007–2016. For the simulation, it provides two significant databases, i.e., PVGIS-CMSAF, and PVGIS-SARAH [19–23]. Hence, this tool with a large database of solar irradiance for major locations allows the users to calculate electricity potentials from the PV power plants with an option of selecting PV technologies (among Crystalline, CIS, and CdTe as shown in Table 3.) installed at a various tilt and azimuth angles.

3.3. Performance parameters

Energy performance of BAPV and BIPV is estimated by considering various parameters: site location, type of the PV technology used, system losses, and loss due to the angle of incidence (AOI_{loss}), loss due to temperature and irradiance ($T\&I_{loss}$). The technical criteria used for the performance evaluation is as follows:

3.3.1. Energy yield (EY)

It is the amount of energy that is produced by the photovoltaic system during the period of operation. E_{AC} is simply referred to the product of voltage and current at the inverter output to the time of operation. Eq. (1) is used to determine the AC energy produced [23–29].

$$E_{AC} = V_{AC} * I_{AC} * \text{time in hours} \quad (1)$$

Table 2
Inputs for the BIPV and BAPV simulation.

Description of Parameter	Input values	
Type of the PV system	Building Integrated Photovoltaics (BIPV)	Building Applied Photovoltaics (BAPV)
Location latitude, longitude	Latitude: 3.544, Longitude: 103.429	
In-plane solar radiation	1850 kW h/Sq. m	
Proposed PV system capacity	32.7 kWp	
PV Technologies	Crystalline (c-Si), CIS, CdTe	
Tilt angle and Azimuth angle	2 degree & 60 degrees	

Table 3
Comparison of photovoltaic modules used in this study [9,22].

PV cell material	Cell color	Efficiency (%)	Advantages
Crystalline	Dark blue, black	13–18	Easily available and more efficient photovoltaic cells
CIS	Black	10–12	Less impact on the performance due to variations in temperatures as well as shadow conditions
CdTe	Dark green, Black	9–11	

3.3.2. Reference yield (RY)

It measures the solar radiation resource for a photovoltaic system. It is the ratio of total in-plane radiation incident on the photovoltaic array to the global radiation at standard testing conditions. Eq. (2) represents the reference yield and it varies as per the geographical location, installation configuration of PV array [23–29].

$$RY = \frac{In\ plane\ radiation\ on\ PVarray\ in\ kWh\ per\ Sq.\quad m}{Global\ radiation\ at\ STCin\ kW\ per\ Sq.\quad m} \tag{2}$$

3.3.3. Yield factor (YF)

It is the ratio of the AC energy generated in kW h (E_{AC}) by the photovoltaic system at the output of the inverter to the nominal installed capacity in kWp. Eq. (3) Shows the expression for calculating the yield factor (YF). This factor can be estimated on the daily, monthly, and annual basis [23–29].

$$YF = \frac{E_{AC}\, in\ kWh}{Installed\ Capacity\ in\ kWp} \tag{3}$$

3.3.4. Capacity utilization factor (CUF)

It is shortly denoted as CUF which is considered as an important parameter for photovoltaic system operation. It is one of the performance factors expressed regarding annual energy generation. Eq. (4) Shows the expression for calculating CUF, and it is defined as the ratio of AC energy generated (final output) by the photovoltaic system over the year to the maximum possible energy generation for a year under ideal working conditions [23–29]. However, CUF does not account for other factors like variations in solar radiation due to the location, temperature, the angle of incidence, etc.

$$CUF = \frac{YF}{365*24} \tag{4}$$

3.3.5. Performance ratio (PR)

Performance ratio is widely accepted parameter by the international community for analyzing the performance of photovoltaic systems. It is the quality factor of the photovoltaic system expressed in percentage. It is defined as the ratio of yield factor to the reference yield. PR, shown in Eq. (5), accounts for various factors like solar radiation, module temperature, grid connection mode, area of the array while analyzing the energy performance of the photovoltaic systems [23–29]. It is a very valuable tool to relate PV plants performance throughout the world as it directly reveals the quality of construction and maintenance.

$$PR = \frac{YF}{RY} \tag{5}$$

3.3.6. Effect of angle of incidence

It is a known fact, that the radiant light energy from the sun generates the photocurrent upon striking the surface of the photovoltaic module. The light energy from the sun will always hit the module by creating an angle away from the normal of a photovoltaic module surface. The reflectively of the radiant energy increases at the module surface which neither responsible for generating photocurrent nor the heat. Hence there will be a considerable amount of losses in the output energies of the photovoltaic system. Hence it is advisable to consider the effect of angle of incidence during the performance studies of the PV system. Martin and Ruiz [30,31] proposed a model to evaluate the angle of incidents effects, which is normally used in the PVGIS simulation [32].

3.3.7. Spectral effects

In the photovoltaic modules, the spectrum of the incoming radiant light energy of the sun has to be taken into consideration during the performance studies. The conversion efficiency of each photovoltaic module in a PV system will depend on the spectrum of the sunlight. The output of the modules in a photovoltaic system will be different if the spectrum of the incoming light is different from the standard at the site of the PV plant installation for a particular time. So, it is necessary to estimate the effective incoming radiations during the studies. As per the IEC-60904-3 standards [33], the spectrum of the light is specified at the module side under the standard testing conditions. For accounting the spectral effects, few models were proposed by various authors [34–36]. Among these models, one model is chosen for this study, and it is presented in the Eq. (6). [37]

Table 4
Coefficients for the PV module temperature and PV Power model [19,32,38–40].

PV Technology	Coefficients for Faiman model		Coefficients for the PV power model					
	U_o	U_1	m_1	m_2	m_3	m_4	m_5	m_6
Crystalline	30.02	6.28	− 0.017237	− 0.040465	− 0.004702	0.000149	0.000170	0.000005
CIS	22.19	4.09	− 0.005554	− 0.038724	− 0.003723	− 0.000905	− 0.001256	0.000001
CdTe	23.37	5.44	− 0.046689	− 0.072844	− 0.002262	0.000276	0.000159	− 0.000006

$$I_{eff} = I^* \frac{\int S_r(\lambda)^* R(\lambda)^* d\lambda}{\int S_r(\lambda)^* R_{STC}(\lambda)^* d\lambda} \tag{6}$$

where, I_{eff} is the effective irradiance, S_r is the module spectral response, λ is the wavelength, here the spectrum R_{STC} is the scaled to make the broadband irradiance as same as broadband irradiance I. When the effect of spectrum is considered, the in-plane irradiance is replaced by the effective irradiance I_{eff} which is calculated using Eq. (6).

3.3.8. Effect of module temperature

In the photovoltaic systems, the performance is affected by the temperature of the modules. As the day progress, the module temperatures rise with the increase of the input irradiance on the modules. The modules temperatures become higher than the ambient temperatures. Hence, it is another important factor to be considered during the performance studies. It is the function of input irradiance and wind speeds of the installation site [27,32]. For a given site, based on the wind speed and ambient temperature, the module temperature is estimated using the Faiman model [38] represented in Eq. (7).

$$T_{PV\,Module} = T_{Air\,Temperature} + \left(\frac{Irradiance\ on\ the\ PV\ module}{U_o + U_1{}^* W_S}\right) \tag{7}$$

In Eq. (7), the coefficients U_o, and U_1 will vary as per the module types. In this study, CdTe modules are considered for the analysis. Hence the coefficients for this module alone is considered and shown in Table 4.

3.3.9. Effect of change in irradiance and module temperature

The PV performance is a function of the change in irradiance value incident on the modules and its temperature. Hence, the power output of the module has to be expressed as a function of these two parameters [32]. Using Eq. (8), the effect of a change in irradiance and module temperature over the energy outputs can be estimated. This expression looks like a regression equation with coefficients that vary with the module technologies and are shown in Table 4.

$$P(I', T') = I' P_{STC}(1 + m_1 \ln(I')) + m_2(\ln(I'))^2 + m_3 T' + m_4 T' \ln(I') + m_5 T' (\ln(I'))^2 + m_6((T'))^2 \tag{8}$$

$$I' = \frac{I}{1000 \quad W. \quad m^{-2}} \tag{9}$$

$$T' = T_{PV\,Module} - 25°C \tag{10}$$

Eq. (8), Eq. (9), and Eq. (10), helps in calculating the effective power from the PV modules after considering the effect of irradiance and temperature. In Eq. (8), the coefficients m_1 to m_6 are determined using the measured data by regression fitting. In this

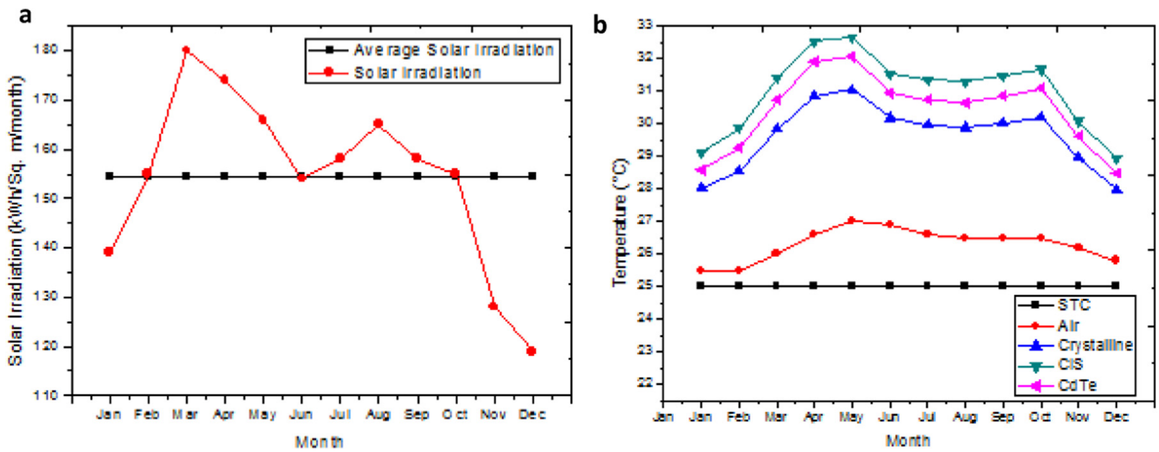

Fig. 2. a). The average monthly sum of solar irradiation (kW h/Sq. m/month); b). Monthly average air and PV module temperatures (°C).

study, these coefficients are taken from the existing literature [19,40].

4. Results and discussion

4.1. Weather parameter analysis

It is well understood that the weather parameters at the installation site will be the significant parameters influencing the performance of the photovoltaic system. The solar irradiance and the air temperature effect on electricity generations throughout the year is studied.

Fig. 2. (a) shows the average monthly sum of the global irradiation in kW h/Sq m. Yearly in-plane solar irradiance for the selected study location is 1850 kW h/Sq;m. The average monthly sum of global solar irradiance at the study location varies between 119 kW h/Sq m (December) to 180 kW h/Sq m (March). However, a slight variation in solar irradiance is observed among various months and the average of all the months is 154.25 kW h/Sq m. The monthly average temperature in the study location is shown in Fig. 2**. (b)** Here, monthly average air temperature, minimum air temperature, the maximum air temperature varies with a slight difference. The monthly average temperatures are observed to vary from 25.5° to 27°C. Similarly, maximum and minimum air temperatures for the same location varies from 28° to 24.5 °C [41]. Wind speeds are in the range of 1.75 m/s (April) to 3.98 m/s (January). This parameter is considered to study the effect of wind speeds on module temperatures from which the effect of temperature on the performance of BAPV and BIPV system can be evaluated. However, there is a slight variation on a monthly basis and average wind speeds of all the months is 2.73 m/s [41]. The energy generation is a function of the irradiance and the temperature as shown in Eq. (9) to Eq. (10). As the intensity of the solar irradiance falling on photovoltaic modules increases, the electron-hole pair generation starts in the photovoltaic cell resulting in the form of current. However, there is an effect of the temperature which reduces the electricity generations. The obtained results of BIPV and BAPV systems with Crystalline, CIS, and CdTe photovoltaics technologies were analyzed based on performance parameters.

4.2. Performance analysis of BAPV and BIPV

4.2.1. Variations in energy generation

The average monthly energy productions from the proposed BAPV and BIPV systems using Crystalline, CIS, CdTe technology were evaluated, and the same is shown in Fig. 3.

The maximum possible energy recorded in March, i.e., 4240 kW h and the minimum energy is 2840 kW h in December for crystalline based BIPV system. The same crystalline modules under similar climatic condition installed as BAPV system generates the maximum possible energy of 4420 kW h in March and lowest possible energy of 2930 kW h in December. BIPV system with CIS technology is observed to perform better than crystalline technology with the maximum possible energy of 4280 kW h in March and minimum energy of 2840 kW h in December. When the system was simulated as BAPV system under similar conditions, the monthly energy generations are quite higher with a maximum possible energy of 4380 kW h for March, and minimum possible energy of 2890 kW h for December. The monthly energies of CdTe as BIPV and BAPV systems are quite high compared to CIS, and crystalline. CdTe technology as BIPV system generates maximum energy of 4490 kW h in the March and minimum energy of 2940 kW h in December. If the same system using CdTe technology installed as BAPV, the system performance is observed to the have maximum energy generation as 4570 kW h in March and minimum energy generations in December, i.e., 2970 kW h. From the analysis, variations in the energy productions were observed for both configurations as well as the PV technology.

In comparison with the BIPV system, it is observed that the energy production and performance is considerably higher for BAPV

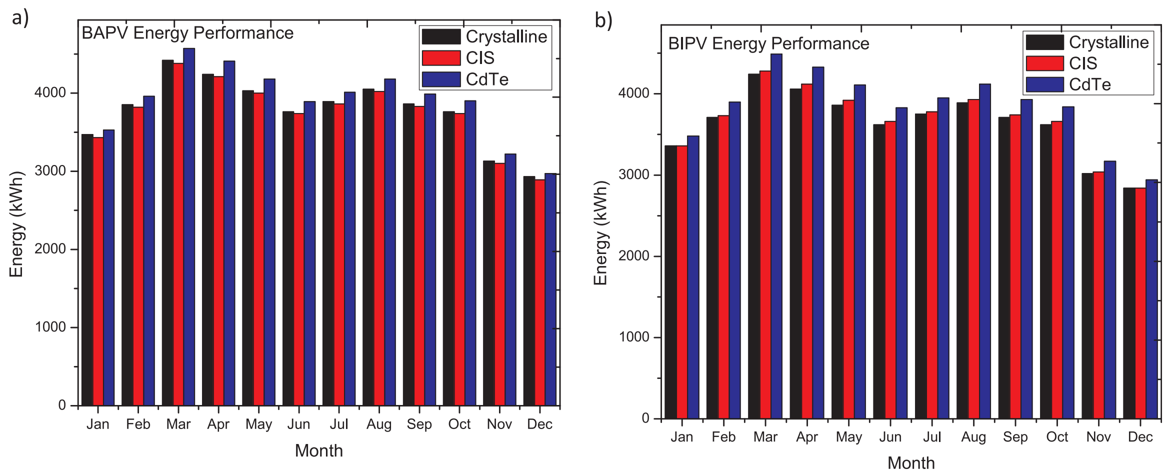

Fig. 3. a). Average monthly energy from BAPV with c-Si, CIS, CdTe in kW h; b). Average monthly energy from BIPV with c-Si, CIS, CdTe in kW h.

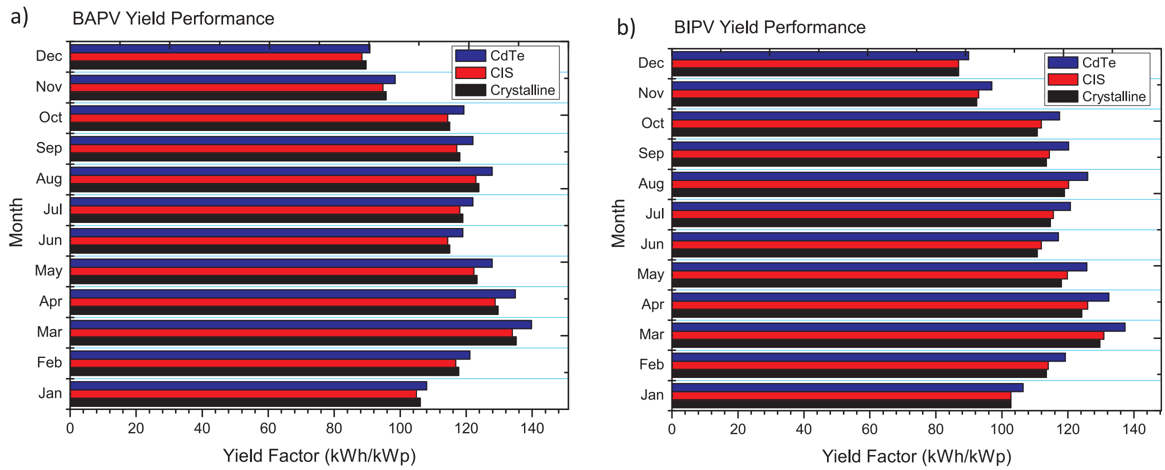

Fig. 4. a). Average monthly yield factors from BAPV with c-Si, CIS, CdTe in kW h/kWp; b). Average monthly energy from BIPV with c-Si, CIS, CdTe in kW h/kWp.

system due to the fewer losses in the system. The annual energy productions of BIPV and BAPV systems with crystalline technology is observed to be 43,680 kW h/year, and 45,390 kW h/year. In a similar manner with CIS technology, the annual energy productions of BIPV and BAPV systems were recorded to be 44,060 kW h/year and 45,020 kW h/year respectively. When the same systems were analyzed with the CdTe technology, the energy productions are observed to be 46,090 kW h/year for BIPV system, and 46,180 kW h/year for BAPV system. In comparison with three different PV technologies, CdTe performs better than CIS, and CIS performs better than Crystalline with the performance order as CdTe, CIS, and Crystalline.

4.2.2. Variation in yield factors

In order to define the overall yield performance of BIPV and BAPV systems, yield factor (YF), were evaluated using Eq. (3). The average monthly yield factors of BIPV and BAPV systems with crystalline, CIS, and CdTe technologies were shown in Fig. 4. The average yield factors represented in kW h/kWp for BIPV and BAPV systems with crystalline technology is 111.31 kW h/kWp and 115.6727 kW h/kWp respectively. Similarly, with CIS technology the average yield factors are 112.28 kW h/kWp, and 114.7298 kW h/kWp, and for CdTe technology 117.46 kW h/kWp, and 119.2915 kW h/kWp respectively.

4.2.3. Variation in CUF and PR

In order to define the overall yield performance of BIPV and BAPV systems, Capacity utilization factors and performance ratios were evaluated for each configuration. Capacity utilization factors were evaluated using the Eq. (4), and are shown in Fig. 5, for crystalline, CIS, and CdTe technologies respectively. The average capacity utilization factors for BIPV and BAPV plants were 15.24% and 15.84% with crystalline technology, 15.38% and 15.71% with CIS technology, and 16.08%, and 16.34% with CdTe technology respectively.

The parameter, which describes the overall performance of the BIPV and BAPV system is the performance ratio (PR). PR denotes the effect of various losses on the output energy yields of the system. It is a dimensionless parameter defined as the ratio of output AC

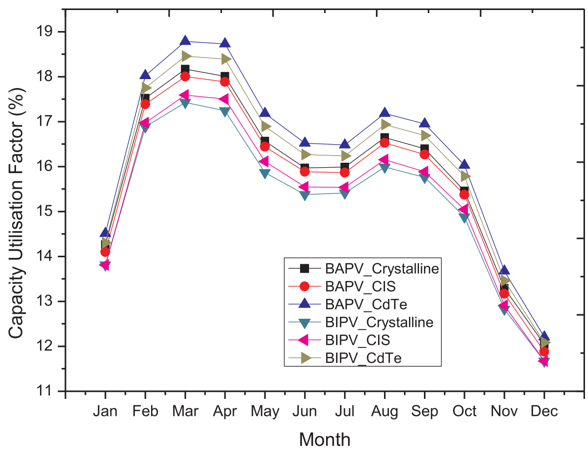

Fig. 5. Capacity utilization factor of BIPV and BAPV systems with c-Si, CIS, and CdTe.

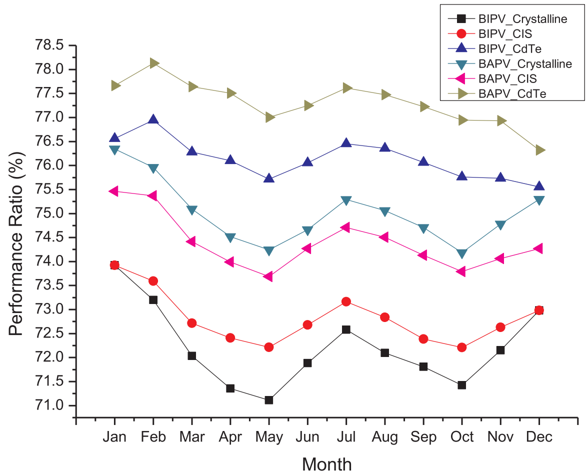

Fig. 6. Performance ratios of BAPV and BIPV systems with c-Si, CIS, and CdTe.

energy delivered to the grid to the DC energy production levels possible at standard testing condition (STC), i.e., 25 °C temperature, 1000 W/m^2, airmass 1.5. PR of BIPV and BAPV systems for each technology were evaluated using the Eq. (5).

The monthly performance ratios of BIPV and BAPV system with crystalline technology is shown in Fig. 6. PR of the BIPV with crystalline technology varies from 71.11% to 73.92% with an average performance ratio of 72.16%; for the BAPV system with crystalline technology, PR varies from 74.18% to 76.34% with an average value as 74.90%. The range of PR for BIPV with CIS technology varies from 72.21% to 73.92% with an average performance ratio of 72.79%, and for BAPV system this variation is around 73.68–75.46% with an average performance ratio as 74.37%. The range of PR variation for BIPV is between 75.55% and 76.94% with an average of 76.14%; for BAPV, this variation is observed to around 76.32–78.12% with an average of 77.33%.

4.2.4. *Loss Analysis*

Overal systems losses in various forms such as the effect of angle of incidence, spectral effects, effects of change in irradiance and module temperatures for the proposed BIPV and BAPV system with three different PV technologies were evaluated using Eq. (6) to Eq. (10). The various losses were quantified and are shown in Table 5.

Considering the angle of incidence losses (AOI) which arises when the light is incident on the PV module at certain angles normal to the surface, and this results in the loss of energy in the form of current or heat. This loss for the BIPV and BAPV system is observed to be −2.8%. It is also observed that the spectrum of the incoming sunlight will affect the energy conversion. The range of this loss is estimated from the simulation studies is around −1 to −5%. Another important parameter that significantly affects the PV system performance is temperature. During the BIPV or BAPV system operation, the temperature of the module rises gradually above the ambient or air temperature of the site location. The module temperature is evaluated by considering the local weather parameters like wind speed, air temperature, solar irradiance on the PV module using Faimen model represented in Eq. (7). The temperature effect is the direct effect caused due to changes in the irradiance. The combined effect of temperature and irradiance is estimated using Eq. (8) to Eq. (10). Losses because of changes in irradiance and temperatures are observed to vary concerning the PV technology. The loss due to this in the crystalline technology used as BIPV and BAPV systems are observed to be −13.6% and −10.2% respectively. Similarly, for CIS technology, it is observed to be −12.8% and −10.9%, for CdTe technology −8.8 and −7.4%. From the comparison of all technologies, it is observed that the CdTe module has a lesser impact due to changes in irradiance and temperatures followed by CIS and crystalline modules.

Table 6 shows the standard deviation of the monthly electricity production for BIPV and BAPV separately for each technology. This is quantified to show the variation of energy from year to year as per the PV system might perform for its lifetime. It is observed that the variation from year to year is possible in the range of kW h for several months. For BIPV system with crystalline technology

Table 5
Effect of AOI, spectral effects, and effects of temperature and irradiance.

Parameter	Changes in output (%)					
	Crystalline		CIS		CdTe	
	BIPV	BAPV	BIPV	BAPV	BIPV	BAPV
Effects of AOI	− 2.8	− 2.8	− 2.8	− 2.8	− 2.8	− 2.8
Spectral effects	1–5	1–5	1–5	1–5	1–5	1–5
Effects of temperature and irradiance	− 13.6	− 10.2	− 12.8	− 10.9	− 8.8	− 7.4

Table 6
The standard deviation of the monthly electricity production.

Month	The standard deviation of the monthly electricity production due to year-to-year variation (kW h)					
	Crystalline		CIS		CdTe	
	BIPV	BAPV	BIPV	BAPV	BIPV	BAPV
January	266	281	274	282	296	303
February	489	518	501	519	542	555
March	408	430	411	429	447	458
April	285	302	288	301	312	320
May	321	339	328	338	349	357
June	244	256	247	255	264	270
July	162	168	161	167	173	176
August	167	178	170	177	180	185
September	202	214	205	213	221	226
October	321	339	329	339	351	359
November	308	323	315	323	337	344
December	348	365	354	365	381	389

variation is seems to be higher in February, i.e., 489 kW h and minimum in July, i.e., 162 kW h; for BAPV system maximum variation is 518 kW h in February, and minimum variation is 168 kW h in July. This variation is observed to be slightly higher for CIS modules when compared to crystalline. In the same way, this value is quite high for CdTe when compared to the other two technologies. The standard deviation of monthly electricity production due to a year to year variation for CIS technology when used for BIPV system is observed to vary from 161 to 501 kW h. For the BAPV system, this is between 167 and 519 kW h for the months July and February respectively. Similarly, when CdTe technology is used for BIPV system, this is observed to be 173 kW h and 542 kW h for July and February and for BAPV system it is observed as 176 kW h and 555 kW h for July and February respectively.

4.2.5. Performance summary of BAPV and BIPV

Annual performance comparison of the proposed BIPV and BAPV system with three technologies used were presented. Table 7 summaries the performance of both systems highlighting the major parameters: annual energy productions in kW h, year to year energy production variability in kW h, yield factor (YF), capacity utilization factor (CUF) in %, losses in % and Performance ratio (PR) in %. Among the proposed two system BAPV system performs better than BIPV, and technology wise CdTe performs better than CIS, and Crystalline.

5. Conclusions

In this study, a 32.7 kWp BIPV and BAPV system with three different PV technologies (crystalline, CIS, CdTe) is simulated using PVGIS to analyze the performance under tropical weather condition of Malaysia. From this performance study of BIPV and BAPV, the following conclusions were drawn:

- It is observed that the relative variation of annual energy generation, performance ratio and capacity factor are very much negligible within PV technologies (crystalline, CIS, CdTe) and mounting configurations (BIPV and BAPV).
- The calculated annual energy generations, performance ratios, and capacity factors for c-Si, CIS, and CdTe power plants were in the range of 43700 kW h to 46,800 kW h, 72.23–77.36%, and 15.25–16.33% respectively.
- The percentage of deviation in performance parameters between the BIPV and BAPV is observed to be 1.49% for CdTe, 2% for CIS, and 3.74% for c-Si PV technologies respectively.
- Irrespective of the building mounting configuration, CdTe solar cells perform better than CIS, and crystalline solar cells in terms of

Table 7
Annual performance comparison of BIPV and BAPV with c-Si, CIS, CdTe.

Parameter	Performance values on an annual basis					
	Crystalline		CIS		CdTe	
	BIPV	BAPV	BIPV	BAPV	BIPV	BAPV
Annual energy productions (kW h)	43,700	45,400	44,100	45,000	46,100	46,800
Year to year energy production variability (kW h)	1910	2010	1930	2000	2060	2100
YF	1336.39	1388.37	1348.62	1376.14	1409.78	1431.19
CUF	15.25	15.84	15.39	15.70	16.09	16.33
Loss (%)	− 27.8	− 25	− 27.2	− 25.6	− 23.8	− 22.6
PR (%)	72.23	75.04	72.89	74.38	76.20	77.36

yield factor, performance ratio, annual energy generation. The total losses in a CdTe technology were observed to be lower than CIS and c-Si technology.
- Pertaining to installation configuration, BAPV performs slightly better than the BIPV for the tropical conditions in Malaysia.
- Based on these outcomes, it concluded that CdTe is the best technology compared to most widely used PV technologies (c-Si) and the existing buildings can be turned into power stations with this approach of BIPV and BAPV.

This analysis provides useful estimates of BIPV and BAPV performance for planning purposes and provides valuable inputs for the development of new policies and innovative solutions for the PV market growth in Malaysia.

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