IN THE FIELD

Performance evaluation of flexible CIGS modules based on operational data under outdoor conditions

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Abstract
As a major driver to achieve feasible long-term goals of the Korean Green New Deal policy, a renewable system application in a building, such as the building-integrated photovoltaics (BIPV) system, has been expedited by raising a BIPV installation subsidy to 70%. Among the technology of BIPV modules, the CuInGaSe₂ (CIGS) type module has been drawing attention and considered as one of the effective alternatives because of its benefits, including its flexibility, lightweights, and relative ease to use as a building material. However, the lack of information understanding of its real application to buildings has still existed under various outdoor experimental conditions. In response to this gap, this study analyzed the power generation performance of flexible CIGS modules under outdoor exposure conditions to evaluate their applicability to BIPV buildings. To conduct the test, the CIGS module was installed on an inclined plane (30°) and vertical plane (90°) using a mock-up installed facing the south. In particular, this study assessed performance ratio (PR) values to analyze the power generation performance behaviors under direct/diffuse irradiance conditions along with diverse cloud cover conditions. Results from this experimental case study indicated that the power generation performance of the vertical CIGS module decreased compared with that of the inclined CIGS module during all analysis periods, except for the February period. This phenomenon became more distinct as the solar altitude angle increased, and the power generation performance of the vertical module became similar to that of the inclined module as the altitude angle decreased. By experimenting with the diffuse irradiance condition depending on the change in cloud cover, the PR decreased by approximately 12%.

KEYWORDS
building-integrated photovoltaics (BIPV), CuInGaSe₂ (CIGS), performance ratio, solar altitude angle
1 | INTRODUCTION

The importance of renewable energy has gradually increased in Korea since the recent announcement of the Green New Deal policy. In addition, the Korean Ministry of Environment (KME) emphasized expanding the supply of renewable energy to achieve the “2050 Long-term Low-greenhouse Gas Emission Development Strategies” under the Paris Agreement goals. KME also committed to increasing the proportion of renewable energy to meet annually increasing electricity demand due to abnormal temperature events and accelerate the reduction in greenhouse gas emissions. The application of solar power systems that can supply economical and stable energy is the most appropriate solution for achieving the environmental policy and addressing the climate change problem. Moreover, the global photovoltaic (PV) market has been gradually growing and is anticipated to reach more than 8.1% of the annual average growth by 2025. The need for residential PV systems is forecasted to expand the most. Additionally, the steady decline in PV prices following the continuous increase in module output has played an important role in the growth of the PV market.

Although the application of PV systems is a realistic solution, there is still an issue in most cases that installing a PV system requires a large land area. Many advanced technologies for PV applications have been developed to address such problems, including floating PV systems and submerged PV systems. However, these systems are not viable alternatives for reducing loads of residential and commercial buildings mainly concentrated in inland Korea because these systems require either a sea or a nearby water stream. Alternatively, BAPV (building-applied photovoltaic) or BIPV systems are widely acceptable for building applications that can be effectively applied to various parts of buildings, including rooftops, windows, and vertical surfaces. Such applications can also contribute to achieve the environmental policy and address the climate change issue. In Korea, a subsidy of the BIPV installation by the government has increased up to 70% of the total installation cost, thereby strongly recommending its installation of the renewable energy systems to building owners. Although the support by policymakers has been increased to encourage renewable energy supplies for moving toward such long-term energy-efficient goals, building owners and designers have been concerned about design and engineering aspects for the applications of relatively new renewable technologies to buildings. With the issues with design and engineering perspectives, PV modules are typically placed on the rooftop of a building to avoid heterogeneous façade design and systems. If technologies can overcome the issues, the application of PV systems to buildings would be accelerated.

CIGS modules (ie, Cu (In, Ga) (S, Se)2) are one of the promising alternatives for BIPV applications due to their benefits, including lightweights and flexible thin-film solar cells. In addition, because the CIGS module of the BIPV applications consists of a flexible thin film for the front cover, the effects of the broken front cover are relatively less than the glass cover. Since CIGS modules’ manufacture process is less complex than the 1st generation of PV modules (eg, crystalline silicon PV modules), the cost is less expensive than other modules. Kong et al. conducted the economic and performance analysis of CIGS modules compared with silica-based BIPV modules. They presented that CIGS PV modules for building applications showed high product competitiveness, acceptable cost, attractive appearance, and environmental benignity. Chantana et al. investigated the various back electrodes to improve PV performance based on a lift-off process. Their study noted that the flexible CIGS modules had no cracks in the superstrate-type CIGS solar cells after the lift-off process. The contact between the CIGS absorber and Au back electrode also demonstrated the ohmic features with low resistance. Furthermore, Paetzold et al. quantified the various losses in CIGS modules and identified the future potential of the modules. Their study observed that although there are key challenges of the technology toward very high-power conversion efficiencies, the CIGS modules are a promising alternative over the other thin-film PV module technologies such as amorphous silicon-based modules.

CIGS is known as a next-generation solar module. CIGS compound semiconductor thin films, buffer layers, and a transparent upper electrode are coated on a glass substrate or a flexible substrate, such as metal foils and thin, flexible surfaces ceramics. According to the previous studies on the CIGS efficiency, an exceptional efficiency of 22.9% was achieved, and it was shown that even 27.5% efficiency could be achieved through an optimization process. There are ongoing studies about power generation characteristics and efficiency based on new structures, such as graphene film-based CIGS or CIGS deposited on stainless steel substrates. Furthermore, the efficiency of CIGS modules can be expected to be enhanced and complemented by successfully developing highly efficient CIGS. Again, CIGS modules can accommodate the aesthetic elements of buildings, making them the most suitable PV module for BIPV systems. From consumers’ perspectives, such as building owners and designers, aesthetics is an extremely important factor. The CIGS as a BIPV module is gaining attention as it can realize irregular structures and be used as a substitute for building components and be integrated with other features.

CIGS modules can be manufactured in a wide variety of ways, such as the sputtering and evaporation of vacuum
process, spray pyrolysis of evaporating and decomposing precursor solution droplets, and atomic layer deposition by chemical reaction-based deposition method. CIGS solar cells are high-quality solar cells with minimal leakage current and noise characteristics with a bandgap of ≥1.2 eV, which have the potential to compete with silicon solar cells. However, the application of CIGS as a BIPV module is still limited, and the lack of information to adopt BIPV applications by building owners and engineers. For example, Mufti et al. pointed out that there is still difficulty in reaching high-quality and large-scale CIGS-based modules for commercialized applications. For field applications of CIGS modules, it would be expected that the efficiency of the commercial CIGS modules is much lower than the obtained laboratory-scale CIGS. Based on such literature, it reveals that empirical studies on the efficiency of CIGS modules in a practical manner are still needed to understand adopting CIGS BIPV applications and investigating the optimal capacity for appropriate field applications. The performance of BIPV systems depends on the installed conditions and external environment, including module surface’s angles and diffuse or direct irradiance. The importance of on-site evaluation has been demonstrated through current existing studies on power generation characteristics according to the environmental factors such as inclination and latitude of the module and through power generation performance studies on the influence of irradiation and ambient temperature. The studies related to the outdoor experiment of the CIGS module had also shown that the power generation performance decreased or the measurement error increased compared with crystalline modules. However, most studies include outdoor field tests for certain limited test periods. In addition, there is no detailed investigation over the various outdoor conditions for a long-term period. There have been not many results that have been identified through long-term measurement experiments outdoors.

Although several studies have investigated CIGS module’s performance, including simulation modeling or empirical laboratory tests, the scope of CIGS modules’ field tests has been limited. There is still a lack of studies understanding the adoption of the CIGS module’s characteristics and improvement for BIPV applications effectively. Such issues have been explored by the literature studies to identify the unexpected reduction in power generation regarding angle-dependent losses. Geisemeyer et al. pointed out that the angle-dependent loss could be a major issue with practical PV generation performance. Karthick et al. conducted a study on reducing surface temperature through phase change material and improving power generation performance accordingly. Plag et al. also addressed the spectral-angular mismatch corrections that should be considered for high-accuracy measurement and its performance on a PV system under outdoor irradiance conditions on a case-by-case basis. Therefore, this study evaluates the CIGS module’s performance under realistic irradiance conditions, depending on the different angles and temperature conditions. The measurement under the outdoor condition is conducted for eight (8) months (eg, Feb. through Sep.) to obtain generated power data from a CIGS PV module based on two separate installation angles (eg, vertical and inclined conditions).

2 | METHODOLOGY

2.1 | CIGS module and experimental test facility

In this study, a CIGS PV module (Miasole, flex series, 02NS, USA), which was a flexible module laminated with ethylene tetrafluoroethylene (ETFE) film, was installed on an inclined plane (tilt: 30°) and vertical plane (tilt: 90°), as shown in Figure 1. As shown in Figure 2, the flexible CIGS module attached to a steel plate was installed on a vertical plane and an inclined plane of the test mock-up, and the experiment was conducted with the fixed modules. The CIGS module, from an undisclosed manufacturer, with an efficiency of 15% and a size of 1722 (L) ×363 (W), was used in the experiment for this study. Table 1 provides the specifications of the modules. As shown in Figure 2, irradiation meters (Delta Ohm, LPPYRA10, Germany) were installed on each inclined plane to measure the irradiation. The measured data were used to analyze the development potential of the test modules. Three irradiation
meters were installed on the horizontal, inclined, and vertical planes to measure the irradiation under each condition, as shown in Figure 2. A CIGS module, each on the inclined plane and vertical plane and a reference crystalline module, was installed, and each of the three irradiation meters was installed on the horizontal plane (0°), inclined plane (30°), and vertical plane (90°). The mock-up was located at 36°21′11.5″N, 127°18′02.7″E with a south direction. The experiment was conducted for eight (8) months, from February to September 2020.

Shading analysis was conducted first using a shade-measuring device to identify the surrounding environment’s shading effects before the experiment. A portable shade-measuring device, SunEye (Solmetric, SunEye10, USA), was used to provide monthly irradiation capacity data using its embedded software. The shading analysis revealed that shading occurred in the mornings and late afternoons during the winter season from January to March and from October to December, as shown in Figure 3. However, in the data analysis, the hours from 10 AM to 4 PM, which is stable enough to collect irradiation to a certain level (200 Wh/m²), were analyzed; thus, the experiment of this study was not affected by the shading effects.

### 2.2 Monitoring system

The TNE TECH manufacturer (PV module monitoring system, South Korea) multichannel testing system was used for monitoring as it allows real-time monitoring by

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**Figure 2** Test mock-up and module installation. CIGS_30: CIGS module installed at an installation angle of 30°, CIGS_90: CIGS module installed at an installation angle of 90°, Ref. crystalline_90: Crystalline module installed at an installation angle of 90° for comparison. The mock-up was located facing the south, and an irradiation meter was established with the module.

**Table 1** Specifications of CIGS and reference PV modules

|                | Pmpp [W] | η [%] | Vmpp [V] | Impp [A] | Voc [V] | Isc [A] | A [m²] |
|----------------|----------|-------|----------|----------|---------|---------|--------|
| CIGS_30,90     | 75       | 15.3  | 19.3     | 3.89     | 24.3    | 4.52    | 0.494  |
| Ref. 90        | 180      | 18    | 19.7     | 9.15     | 24.4    | 9.69    | 0.837  |

**Figure 3** Shading analysis results of the test mock-up: (A) shading effects by Solmetric SunEye and (B) monthly data of shading effects.
connecting a local network with a desktop computer. This system comprises 35 channels, including 32 and 3 channels for module characteristics and irradiation data. The actual data were measured for 8 months at a frequency of once per ten (10) min. The specifications of the monitoring system configuration for this study are provided in Table 2.

2.3 | Weather conditions of South Korea

Because South Korea has four distinct seasons: winter (December–February), spring (March-May), summer (June–August), and autumn (September–November), the solar altitude angle varies from a maximum of 76° in summer to a minimum of 29° in winter. In other words, it means that the condition of the angle of incidence varies greatly from month to month. Based on such weather changes, monthly irradiation conditions can be varied, as shown in Figure 4. This figure shows the comparison for the irradiation of 30-year average standard weather data provided by the Korean Solar Energy Society versus irradiation data directly collected during the measurement period (February to September) to identify the measured irradiation data from the study site with the 30-year average data in the same city. The average error rate between the standard weather data and the measured data was relatively similar, within 5%, except for July and August. Note that the average error rate is relatively high compared with other months because of the rainy season in July and August.

Cloud cover data provided by the Korea Meteorological Administration (KMA) for the measurement period were also considered for this study to capture any potential effects of direct and diffuse solar conditions on CIGS power performance. Figure 5 presents the average cloud cover patterns of each month. Based on the monthly trends, cloud cover was analyzed as over 5 on average during the summer, indicating many cloudy days. Cloud cover data were used further for the sensitivity analysis of the cloud cover.

2.4 | Data analysis

The raw data obtained from the experimental facility were analyzed with hourly, daily, and monthly time horizon. The testing system measured and stored the data every 10 min (ie, irradiance by the angle through each irradiation meter, temperature data at the rear of the module [steel plate], maximum power [Pmax], maximum voltage [Vmpp], maximum current [Impp], open-circuit voltage [Voc], and short-circuit current [Isc]). Although the

| Table 2 Description of the outdoor test system of PV module |
|-----------------|
| (1) MPPT I–V Measurement unit |
| - MPPT Mode |
| - I–V Mode |
| - 300 V, 20 A, 600 W |
| (2) Temperature DAQ |
| - Module Temperature 32 ch |
| - T type |
| - 16 bit ADC |
| (3) Temperature sensor 32 set |
| - Temperature sensor 32 set (T type 10 m) |
| (4) Main system |
| - Control PC |
| - System Software: |
| - I–V parameter, PV generation, Irradiance, Temperature record |
| - Data interface Unit |
| - 19 inch rackmount |
| (5) Monitoring data |
| - Maximum power output, Pmpp (W) |
| - Maximum power voltage, Vmpp (V) |
| - Maximum power current, Impp (A) |
| - Open circuit voltage, Voc (V) |
| - Short circuit current, Isc (A) |
| - Fill factor, FF (%) |
| - Module-level I–V curve |
| - Horizontal plane irradiation (W/m²) (0° tilt angle) |
| - Inclined plane irradiation (W/m²) (30° tilt angle) |
| - Vertical plane irradiation (W/m²) (90° tilt angle) |

**Figure 4** Comparison of the analysis result of the monthly horizontal plane irradiation data in the Daejeon area (30-year standard weather data provided by KSES) and the measured irradiation during the experiment period
experiment was conducted for 8 months from February to September, the CIGS_90 module was measured for six months only, excluding the measurement errors for 2 months in June and July. The average value at a specific hour range was derived and analyzed to remove variables for each analysis. The power generation performance was compared by calculating the performance ratio (PR) value using the amount of power generation compared with the irradiance in each module for each installation angle. PR is an international key performance indicator and the most reasonable analysis method that allows comparisons between different climatic conditions. The PR was calculated using the following equation:

\[
PR = \frac{P_{\text{max}}}{W_p} \times \frac{G_{\text{STC}}}{G_{\text{POA}}}
\]

where \(P_{\text{max}}\) = Maximum power (W), \(W_p\) = DC peak power rating (W), \(G_{\text{STC}}\) = Global solar irradiance under standard test condition (1000 W/m²), \(G_{\text{POA}}\) = Average solar irradiance in plane of array (W).

3 | RESULTS AND DISCUSSION

3.1 | I–V factors of the CIGS module on plane temperature and irradiance

A sensitivity analysis was performed to evaluate the power generation performance of the CIGS module based on two major factors, including the module’s temperature and solar irradiation in this section. The temperature coefficient of CIGS is superior compared with general crystalline silicon modules. To minimize the errors due to varying irradiation levels, typically in the early mornings and late afternoons, only the data measured between 10 AM and 4 PM, which are the hours of stable irradiation, were used for the data analysis.

As shown in Figure 6A, through the analysis depending on the irradiation, although the voltage increased with the increase in the amount of irradiation, the voltage decreased slightly when it exceeded a certain range. For example, after 800 Wh/m² of irradiation, the curve line tended to show descending a slope. However, the current presented a strong relationship between the irradiation and Impp values by increasing proportionally and the increased irradiation amount, as shown in Figure 6C. Examining Figure 6B,D, the temperature analysis revealed that the voltage showed decreased trends as the temperature increased from 30 to 35°C. Conversely, the voltage distribution showed relatively high fluctuations for the temperature range between 0 and 30°C with a slightly positive slope of the curve fitting line. Regarding the cross plot between the module temperature and the current value, the distribution showed even higher fluctuations along with an entire temperature range by presenting clear trends of the gradually increased slope of the curve fitting line. Based on the trends shown in this Figure 6, it can indicate, as expected, that the correlations between the maximum current and irradiation values showed much stronger relationships when compared to those between the maximum voltage and irradiation values for the same irradiation levels. In addition, it can also be noted that both slopes of curve fittings between module temperature...
and voltage values and between module temperature and current values showed stronger relationships. However, the distribution of the current distribution showed significantly higher fluctuations. Since the seasonal variations of the PR could be originated mostly from the solar cells’ seasonal temperature and irradiation oscillations, those output behaviors associated with the module’s temperature and the irradiation are considered for further PR analysis of the PV modules.

3.2 | PR of the CIGS module

Based on the results from the comprehensive analysis described in the previous section and these characteristics, the change in the PR of each CIGS module installed on the inclined and vertical planes was analyzed, as shown in Figure 7. In the inclined CIGS case, although the PR increased with the increase in irradiation, the PR values remained a small decrease during the summer when the irradiation was above 800 W/m². This was expected because the power generation voltage decreased mainly due to the high temperature. For example, when the measured irradiation was above 800 W/m² during the summer season, it was captured that the measured back PV module temperature mostly showed above 42°C on average and even reached 63°C on the maximum value. In the case of the vertical CIGS plane, the measured temperature of the back PV module was kept slightly lower than that of the inclined CIGS module with an average of 24°C and a maximum of 35°C primarily due to the angle of incidence. It thus reduced irradiation, as well as lower outside temperature during the winter period. Therefore, based on the combined results, it can be summarized that the PR values tended to increase accordingly mainly because the voltage affected by the temperature and the current affected by the total irradiation were stable.

3.3 | PV yield under different installed angles

Before analyzing the monthly power generation performance due to diffused irradiance, to remove variables and set the same analysis period for comparison, the same conditions where the insolation at the slope and the vertical surface was ≥200 Wh/m² and PR was ≥0.9 are considered. Figure 8 shows an analysis of the number of hours.

![Analytical results on the correlation of voltage and current according to irradiation and module temperature. (A) Correlation of maximum voltage compared with irradiation. (B) Correlation of maximum voltage compared with module temperature. (C) Correlation of maximum current compared with irradiation. (D) Correlation of maximum current compared with module temperature.](image)
CIGS_30 module exhibited stable power generation performance between 8 AM and 3 PM throughout the study period. However, the CIGS_90 module typically revealed stable power generation performance between 10 AM and 2 PM. Therefore, the data measured between 11 AM and 1 PM were used in the analysis to consider the impact of diffused irradiance specifically.

\[ N_{h,m} = \begin{cases} \sum N, & \text{if } G_{irr} \geq 200 \text{ and } PR \geq 0.9 \\ 0, & \text{otherwise} \end{cases} \]  

where \( G_{irr} \) is the irradiation, \( h \) is the corresponding hour, and \( m \) is the corresponding months. Hence, \( N_{h,m} \) is the number of months and hours that satisfy the conditions mentioned above.

**FIGURE 7** Average PR for inclined plane CIGS (A) and vertical plane CIGS (B) by irradiation section. (A) When the irradiation was above 800 W/m², although the average rear temperature of the module was 42°C and the efficiency decreased due to the increase in temperature in summer during mid-April to July, it showed stable performance owing to abundant irradiation. (B) From February to March, the irradiation averaged over 800 W/m², and the average rear temperature of the module was 24°C, exhibiting high-power generation performance.

**FIGURE 8** Hourly number corresponding to the irradiation of \( \geq 200 \) W/m² and PR of \( \geq 0.9 \).
The solar altitude angle in the analysis hour ranged between a minimum of 27° and a maximum of 75° on an annual basis, and the azimuth angle ranged between a minimum of 117° and a maximum of 171°, as shown in Figure 9.

Figure 10 shows the average daily power generation and the specific yield values of each module. In terms of the power generation for the vertical versus inclined CIGS modules, the power generation was reduced by up to 68% in May. The yield value of the CIGS module was also captured 15% lower compared with the crystalline module (ie, the reference compared module) installed on the same vertical plane.

Figure 11 shows the results of the monthly average irradiation and PR analyses. The analysis in February found that the average PR of the CIGS module installed on the vertical plane showed relatively flatten patterns with that of the CIGS_30 module, exhibiting good power generation performance owing to a large amount of direct irradiation. However, as the solar altitude angle increased to a maximum of 73° during the summer season, the average difference in the PR performance of the vertical plane was approximately 10% as in April and May, and the performance was noticeably degraded. In the case of August, although the altitude angle was the same as in April, the average voltage output decreased, which affected the power generation performance as the temperature of the rear plane of the CIGS_30 module (Module T.) increased to an average of 52°C with a maximum of 64°C or above due to the outside temperature. Contrastingly, the PR performance of the CIGS_90 module improved as the solar altitude angle decreased again. For the reference crystalline module (Ref._90), it was observed that although the temperature of the rear plane of the CIGS_90 module was similar, the PR exhibited stable performance even when the solar altitude angle changed (Table 3).

Although cloud cover changes instantaneously, the experiment was conducted for a more intuitive judgment because it was difficult to determine the effects of diffused irradiance by comparing the power generation values obtained by monitoring with the hourly measurement data provided by KMA.

A simplified solar cell measuring device was connected to the module for the experiment, with the incident angle
installed at 0°. Then, the measurement was performed according to the change in cloud cover during the same hour range. For the experimental equipment, Solmetric PV analysis (IV Curve Tracers) was used. The cloud cover at the time of the experiment is shown in Figure 12, where the measured irradiation around 16:19–20, which was the experimental measurement time, was 543 W/m²; the PR was obtained as 0.85. Furthermore, the irradiation was measured to be 232 W/m² as the cloud cover increased after 7 min. The PR was 0.75, with a decreased power generation performance of approximately 12.7% (Table 4). A distinct difference in the performance of the CIGS module was observed when using the changes in the cloud cover, excluding all the variables such as the module angle, measurement day, and solar altitude angle. Consequently, the CIGS power generation performance decreased when the direct irradiation component decreased and the diffused irradiance component increased.

Figure 13 shows the comparison of the I-V characteristics of simplified CIGS measurement results based on captured irradiation and cloud cover conditions, presented in the experiment condition of Figure 12 and the result of Table 4. Examining this figure, we observed that even if the installation condition was the same for each test time, the performance of the CIGS module’s power generation could be significantly varied according to changes constantly in
the cloud cover levels. This is primarily because of reductions in current levels, which highly depend on irradiation variations from direct and/or diffuse irradiance.

### 3.4 PV performance ratio of the CIGS module under the diffuse irradiance

The results of the three modules’ scatter plot analysis regarding the daily average cloud cover are shown in Figure 14. The scatterplot analysis shows the effect of cloud cover on the PV power generation performance. As the CIGS_30 module was installed at the optimum angle to this location, it was determined that the overall power generation performance of the CIGS_30 module was higher, and the reaction in response to the irradiance condition was relatively smaller when compared to the CIGS_90 module. However, in the CIGS_90 module, the overall power generation performance showed significantly lower due to the vertical installation. The effect of the cloud cover on the reaction was increased according to the irradiance condition. There was a significant difference in the power generation performance and sensitivity between the CIGS_90 and the Ref_90 modules, even if those modules were installed on the same vertical plane. Based on this compared result, it can be expected that the CIGS module is significantly sensitive to the power generation performance under diffused light conditions and the reduction in absolute solar radiation. Such behaviors of CIGS power generation were also captured according to the literature. The result from their experimental study pointed out that a maximum of 7.4% of performance

| Month      | Incidence (°) | Module T. (°C) | PR (-) | Incidence (°) | Module T. (°C) | PR (-) | Module T. (°C) | PR (-) |
|------------|---------------|----------------|--------|---------------|----------------|--------|----------------|--------|
| February   | −19           | 30.7           | 0.93   | 41            | 24.2           | 0.93   | 35.3           | 0.96   |
| March      | −8            | 41.1           | 0.90   | 52            | 38.1           | 0.88   | 39.0           | 0.97   |
| April      | 4             | 43.9           | 0.90   | 64            | 33.9           | 0.80   | 36.0           | 0.96   |
| May        | 10            | 33.5           | 0.90   | 73            | 36.0           | 0.81   | 38.7           | 0.89   |
| June       | 16            | 54.4           | 0.88   | 76            | -              | -      | 40.9           | 0.90   |
| July       | 10            | 44.6           | 0.91   | 73            | -              | -      | 36.4           | 0.91   |
| August     | 4             | 52.5           | 0.88   | 64            | 42.9           | 0.82   | 45.1           | 0.91   |
| September  | −8            | 50.1           | 0.92   | 52            | 40.9           | 0.91   | 43.4           | 0.91   |

The performance ratio (PR) was calculated using the formula $PR = \frac{P_{module}}{P_{ref}}$, where $P_{module}$ is the power output of the module and $P_{ref}$ is the power output of the reference module. The results showed that the CIGS_30 module had a significantly higher PR than the other two modules, indicating superior performance under diffuse irradiance conditions.

**FIGURE 12** Observation of cloud cover changes for measuring the I–V curve of August
TABLE 4 Results of CIGS module performance analysis according to irradiation and cloud cover

| Time  | Irradiance (W/m²) | Pmax  | Vmpp  | Impp  | Voc   | Isc   | Wh/Wp | PR  |
|-------|-------------------|-------|-------|-------|-------|-------|-------|-----|
| (A)   | 16:19             | 543.1 | 36.23 | 16.79 | 2.16  | 21.46 | 2.46  | 0.45| 0.83|
| (B)   | 16:20             | 543.3 | 37.40 | 16.96 | 2.21  | 21.40 | 2.57  | 0.47| 0.86|
| (C)   | 16:25             | 235.6 | 14.16 | 16.00 | 0.88  | 20.26 | 1.07  | 0.18| 0.75|
| (D)   | 16:26             | 228.7 | 13.79 | 15.90 | 0.87  | 20.23 | 1.02  | 0.17| 0.75|

FIGURE 13 Captured I-V curve of CIGS simplified measurement results. (A), (B) I-V curve measurement result when the measurement time is 16:19–16:20. (C), (D) I-V curve measurement result when the measurement time is 16:25–16:26.

FIGURE 14 Sensitivity analysis of power generation performance of each module regarding a cloud cover level.
degradation in a CIGS module could occur based on diffuse irradiance conditions compared with other traditional PV modules. By considering such features of the CIGS module's power generation, it can summarize that CIGS module can present better performance under clear irradiance conditions.

To account for the combined effect of solar conditions and module's temperature and cloud covers on the PR

FIGURE 15 \( \Delta PR_{h,m} \) values of CIGS_30 and CIGS_90 by the hour for each month
variations of the CIGS modules, the difference between two CIGS modules was calculated and compared by time and month corresponding to each representative factor. To calculate the difference values, the \( \Delta PR_{h,m} \) equation is by simply subtracting PR values of CIGS_90 from those of CIGS_30 as follows:

\[
\Delta PR_{h,m} = PR_{CIGS30} - PR_{CIGS90} \tag{3}
\]

where \( PR_{CIGS30} \) and \( PR_{CIGS90} \) are the PR values of CIGS_30 and CIGS_90 modules, respectively. Figure 14 shows the difference between two CIGS modules by selected hour and month to capture the combined effects and relationships between each module's power outputs and external factors.

Figure 15 presents the combined effect on the PR difference values in different factors (eg, solar conditions, modules temperature, cloud cover, and installed positions) that can primarily contribute to the PR variation, calculated using Equation (3). Figure 14 displays four separate graphs, including the comparison of (a) PR differences, (b) irradiation of each plane, (c) cloud factors, and (d) temperature and altitude angles. Combined results from this figure indicate that each month includes its tendency to address why PR differences are varied according to representative hours and months for the 6 months.

Based on the observed PR differences, the greater PR difference value indicates that the CIGS_30 module had greater power generation efficiency than the CIGS_90 module. Although PR values of each plane were calculated based on each plane-of-array irradiance, they presented different PR values between each other. Later, afternoon hours tended to show relatively greater PR differences in most months. For example, the greatest PR difference was presented at 4 PM in September, while the lowest value was captured at around 10 AM hours. This was primarily because the irradiation on the vertical plane module was significantly down, for example, presenting about 200 W/m², which thus made significant degradation of the module's performance compared with the inclined plane case. Such behaviors of power performance could occur for most other month periods as well. In addition, there were lower PR differences, including about 0.1 or below, for February and some hours of March because of the combined effects of low solar altitude angles and cloud cover levels compared with other month period times. In April, the trend of cloud cover levels was similar to March’s, but relatively high-altitude conditions could cause the greater PR difference due to increased PR values of the inclined plane module case. In terms of patterns in May, most PR differences were greater than 0.1 with the highest solar altitude angles, whereas the reduced PR differences were shown during August and September. This was expected that even though the cloud cover levels were relatively high attributed to most diffuse irradiance components due to a rainy season, the solar altitude angles were decreased by close to the normal angle of the CIGS_30 module. Such combined effects could contribute to greater performance of power generation for the inclined plane module.

4 | CONCLUSIONS

This study conducted a comparative investigation analysis on the power generation performance of a flexible CIGS module based on measured data under outdoor conditions. Various outdoor weather components were considered for this study, including irradiation, cloud cover, and temperature conditions. With a rear-steel-mounted construction, the identical CIGS modules with the same specification were separately installed on each plane condition, including inclined (30° of tilt angle) and vertical (90° of tilt angle) positions. Based on such an experimental case study, the key findings are the following:

- With increases in the back-surface temperature, the power generation performance was slightly degraded even when irradiation increased. In the vertical CIGS case, the power generation performance was gradually improved as the amount of irradiation increased because of better incidence angles to the normal direction.
- This comparative analysis also revealed that the CIGS module's generation losses were relatively high under diffuse irradiance conditions than the silicon-based module types. In addition, it should also be noted that the reaction of the vertical CIGS module in response to the cloud cover condition that had high diffuse components of sunlight was relatively greater when compared to the inclined modules (30° tilt angle module).

Such results from this study could provide useful insights into power generation performance degradation of CIGS modules in a specific situation and BIPV design requirements when flexible CIGS modules were considered for building applications. Based on this study, there are several limitations in this study, including that (a) different direct and diffuse sunlight conditions should be considered to show more detailed comparison under the cloud cover conditions, and (b) several months (eg, June, July, and some of the winter months) were missed for measured data. In addition, the overall power generation performance of the CIGS module for more various BIPV applications needs to be analyzed in future research. Diverse installation areas and conditions also need to be thoroughly extended to include an application plan under various weather parameters.
and scenarios. An optimal CIGS module design is also required based on prior information about the solar altitude angle in the proposed installation region for better BIPV applications practically.

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