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Research Article

Characterization of Cost-Saving Monofacial PERC Module under Field Conditions in South Korea

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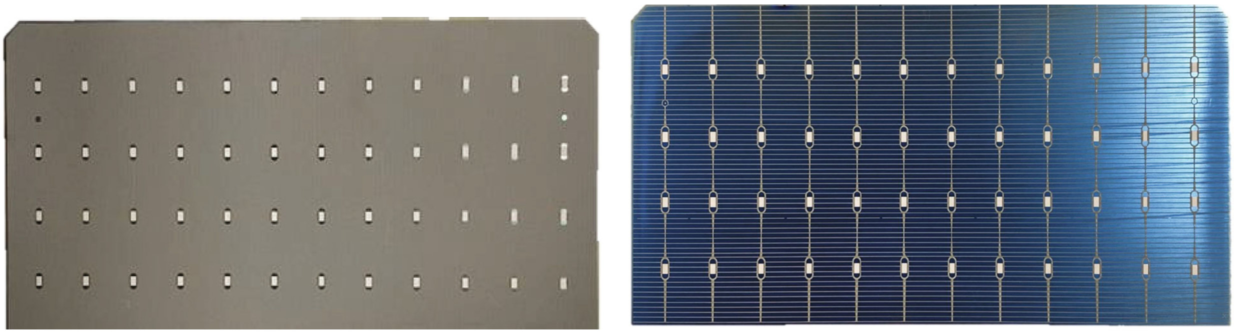
The photovoltaic (PV) industry is constantly striving to increase module power output while decreasing costs. Importantly, the performance and reliability of cost-saving products should be evaluated before being launched into the PV market to avoid any unnecessary side effects. This study investigated the performance of a monofacial module employing a cost-saving bifacial cell installed at a carport in South Korea. The bifacial cell reduces costs, compared to monofacial cell, by using a lower quantity of aluminum paste on its rear; consequently, it has become a popular product in the PV industry. The monofacial module employing the bifacial cell showed an improved voltage temperature coefficient and low-light performance over monofacial cell-based module. Our field data highlight three conclusions from the bifacial cell-based module; it showed (1) different voltage temperature coefficients with better performance at lower temperatures, (2) better low-light performance owing to high series resistance, and (3) high current owing to its bifaciality. Notably, under high irradiance and temperature conditions, the bifacial cell performed worse than the monofacial cell. We concluded that this type of cell may perform well under northern European climatic conditions, though further investigation is required to optimize cell performance under various weather conditions.

1. Introduction

In the photovoltaic (PV) industry, levelized cost of energy (LCOE) is a key parameter that can elucidate the profitability of a PV system considering performance, cost, and reliability [1, 2]. Most research and development have focused on improving device performance (e.g., cell efficiency or module power) using new structures of, for example, perovskite, tandem, and large products with an M10 ($182 \times 182\,mm^2$) or M12 ($210 \times 210\,mm^2$) wafer size. Correspondingly, the market shares of M10 and M12 Cz-mono wafers exceeded 50% in 2022 [3]. Further, because of the superior power and rear light absorption capabilities provided by a bifacial cell structure, the market share of bifacial cells exceeded 60% in 2022 and is expected to be >80% by [3–5].

Cost reduction is an important issue that can contribute toward industry-wide competitiveness and profitability. The PV industry has already made efforts to utilize fewer materials, including aluminum paste. The amount of aluminum paste required for M6 monofacial passivated emitter and rear contact (PERC) cells is currently ~750 mg/cell, whereas that for M6 bifacial PERC cells is much lower (~200 mg/cell) because the paste is only applied to the finger area. Because of recent increases in the market shares of large wafers such as M10 or M12, paste consumption and costs have also tended to increase [3, 6, 7]. Therefore, the bifacial cell structure presents two advantages: more power owing to rear side absorption and reduced costs owing to less paste consumption.

Reliability is related to energy yield, which can inform how long energy can be produced during a specific period [2]. Energy yield can directly affect the LCOE and PV economics. Generally, all PV products pass the reliability test conditions during certification. However, standard test conditions (STCs), certification, or reliability tests do not represent the performance of products in the field; thus, consistent energy yield cannot be guaranteed [8].



(a) (b)

Figure 1: Comparison of rear metal design between (a) monofacial cell and (b) bifacial cell.

Performance, cost, and reliability improvements appear to be independent under STCs. However, product performance is mutually linked according to field data. An improved parameter value could result in side effects, which may not benefit the LCOE. Monofacial modules with bifacial cells have recently been adopted in the PV industry owing to the reduced cost of the bifacial cell compared with that of the monofacial cell. The current market share of monofacial modules with bifacial cells is 20–30% [3]. The bifacial cell can absorb some infrared (IR) radiation through the rear encapsulation layer and backsheet [9] and thus has a different quantity of aluminum paste at the rear than a monofacial cell. This can also affect the temperature coefficient under field conditions. However, the field performance of monofacial modules incorporating bifacial cells needs to be assessed to determine potential side effects not shown under STCs.

This study investigated the field performance of the monofacial module–bifocal cell system installed at a carport in East Asia under ambient temperatures and various irradiance conditions. We finally propose the best setting for optimizing the field performance of this combined system based on our results.

2. Materials and Methods

2.1. Monofacial and Bifacial Cell Structures and Performance. The two cell types in this study had a PERC structure. The front of both cell types had the same wafer specifications, diffusion processes of an n+emitter, an antireflection coating (ARC) with a SiNx layer, a metal design, and silver paste; however, their rear sides differed. One had a metal design, and the other a dielectric structure. For the rear side metal design, the rear of the monofacial cell was entirely covered with silver and aluminum pastes, whereas that of the bifacial cell was not entirely covered with these pastes to enable the penetration of light (Figure 1). The quantity of aluminum paste was reduced from 720 to 250 mg/cell so that some rear light could be absorbed and the thermal budget could be varied between cell products. This can also affect the series resistance and fill factor (FF) and finally contribute to low-light behavior. These effects are further explained in Results and Discussion. The type of aluminum paste was similar for monofacial and bifacial cells.

For rear dielectric structures, the dielectric layers on the monofacial cell were intended to improve (1) the rear side recombination velocity and (2) reflection within the IR range between the silicon and dielectric layers [10]. The rear structure of the monofacial cell comprised p-type silicon/Al_2O_3 (refractive index at $\lambda = 632$ nm: 1.55, thickness: 12 nm)/SiN (2.1, 20 nm)/SiN (2.05, 20 nm)/SiON (1.6, 100 nm)/SiN (2.06, 20 nm). The bifacial cell had the same structural purposes but also had to receive light through the rear. Therefore, the rear structure comprised p-type silicon/Al_2O_3 (1.55, 15 nm)/SiN (2.1, 20 nm)/SiN (2.05, 20 nm)/SiON (1.6, 40 nm)/SiN (2.06, 10 nm), which only differed in terms of thickness. Figure 2 shows the two external quantum efficiency (EQE) spectra of the bifacial cell. With different rear dielectric structures, the EQE spectra of the rear side had lower values to satisfy the three purposes. The EQE spectra for front incident light were similar in both cells [11, 12].

The bifacial cell structure was ~0.15% less efficient than the monofacial cell because of the higher series resistance and lower fill factor (FF) of 82.58% compared with 82.98% in the monofacial cell. This variation is associated with differences in the rear metal design and aluminum paste consumption (Figure 1(b)). The other parameters, such as short-circuit current and open-circuit voltage (Voc), were comparable between cell types.

2.2. Module Structures and Performance. Both cell types had the same monofacial module structure (Figure 3) [13]. The module consisted of a 3.2 mm thick ARC glass sheet laminated with transparent ethylene vinyl acetate (EVA) on the front and white EVA as an encapsulant on the rear, a white backsheet, and one monofacial or bifacial cell. White EVA was used on the rear because of the higher cell-to-module conversion ratio than the white backsheet [9]. The 350 μm thick backsheet consisted of two polyethylene layers on top and a polyethylene terephthalate layer on the bottom.

The electrical parameters of these two modules are presented in Table 1. These values represent the averages across 15 modules of each type. The higher power of the module with bifacial cells (type B) was due to the efficiency of the cells in these modules. The cell-to-module conversion ratios were similar between types. As expected, the module with the monofacial cell (type A) had a bifaciality (i.e., the proportion of energy produced at the rear of the panel

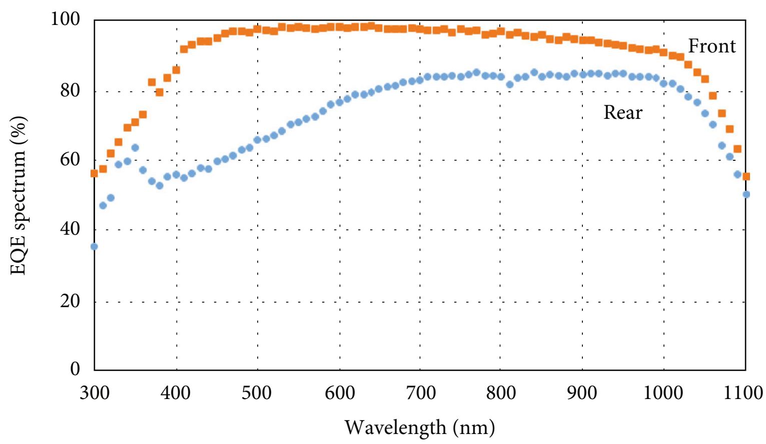


Figure 2: External quantum efficiency (EQE) spectrum comparison for the front incident and rear incident light on the bifacial cell. “Front” indicates the EQE spectrum for front incident light, and “Rear” indicates the EQE for rear incident light.

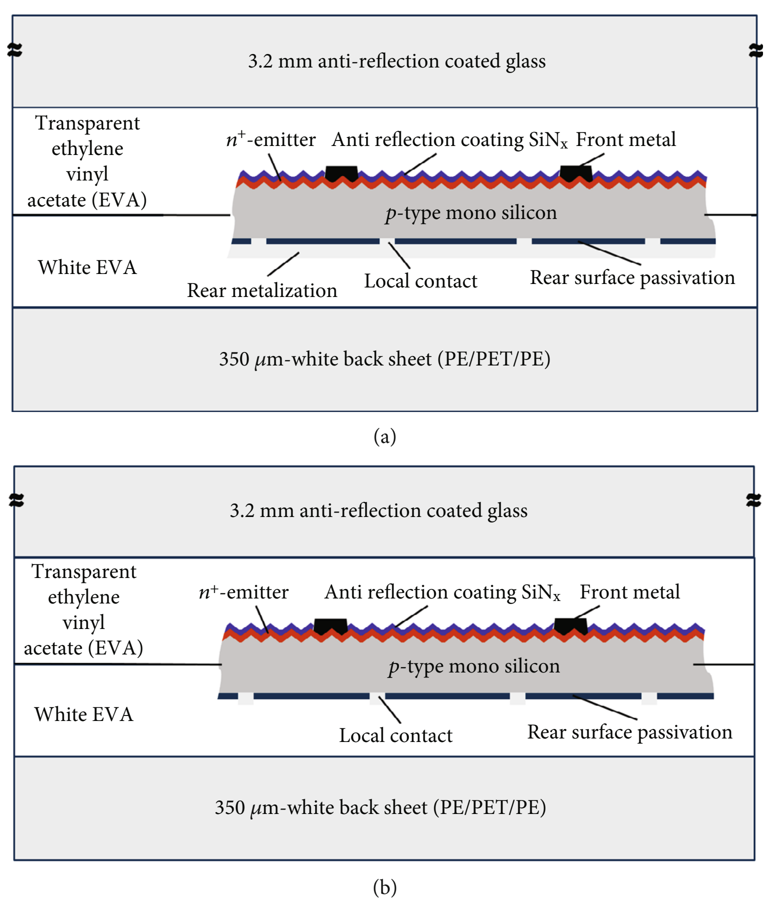


Figure 3: Structure of module with the (a) monofacial cell and (b) bifacial cell.

compared with that at the front of the panel) of 0.47% because the aluminum and silver paste on the back of the cell (Figure 1(a)) effectively blocked light from the rear. On the other hand, type B had a bifaciality of 3.46% because the white backsheet and white EVA had some transmittance, allowing light absorption through the rear. White EVA has more than 10% transmittance over a wavelength of 800 nm, and the white backsheet also has some transmittance [9]. This effect is explained by the energy yield data presented in Results and Discussion.

We installed 15 modules of each type in a carport system in Korea (36° 54′ 26″ N, 127° 28′ 52″ E). The height of the carport ranged from 2.51 to 2.97 m, which enabled a higher energy yield than that achieved in previous studies [11, 14,

Table 1: Electrical parameters of the two modules.

Cell type	Power (W)	Voc (V)[1]	Isc (A)[2]	FF (%)[3]	Bifaciality (%)
Monofacial cell (type A)	422.4	48.63	10.86	79.99	0.47
Bifacial cell (type B)	424.1	48.68	10.93	79.75	3.46

[1]Open-circuit voltage. [2]Short-circuit current. [3]Fill factor.

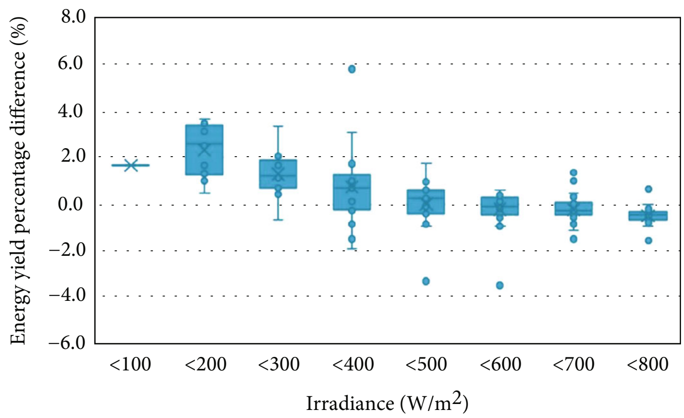


Figure 4: Energy yield percentage difference for the bifacial and monofacial cells according to the level of irradiance.

15]. Each carport had space for three cars, and the system consisted of two adjacent carports equipped with 15 each of type A and B modules. A temperature sensor was located on the cell at the back of each module [11]. The total power generated with type A and B modules in each carport system was 6.34 and 6.36 kW, respectively, according to STC data summation for all modules.

3. Results and Discussion

Figure 4 shows the percentage difference in energy yield between type B and A modules for various irradiance values for 1 month (April 11 to May 10) in East Asia. April and May correspond with spring in Korea. During this one month, the accumulated power was 692.4 and 694.3 kWh for types A and B, respectively, corresponding to an energy yield of 3.642 and 3.638 kWh/Wp/d, respectively. The percentage difference was only −0.12%, meaning the accumulated value was comparable. However, this trend differed under various levels of irradiance. At up to 500 W/m^2, type B modules showed a higher percentage difference in energy yield, while at values >500 W/m^2, type A modules showed a higher percentage difference.

Figure 5 shows a temperature comparison among ambient, type A, type B, and delta between type B and ambient based on the irradiance amount for 1 month. The module temperatures were measured on their backsheet. The type B module showed slightly higher temperatures than type A.

Figure 6 shows the module parameter percentage difference with varying levels of irradiance for 1 month. The percentage difference for the current was always positive, meaning that the type B module had a higher current. This can be explained by the bifaciality value (3.47%) in Table 1. Owing to the bifacial cell allowing some transmittance with the white EVA and white backsheet, the type B module can generate more current [9]. At low irradiance, the percentage difference tends to be greater, indicating that the type B module can be advantageous in terms of current generation at lower levels of irradiance [14, 16–18].

Notably, voltage exhibited a different behavior. The voltage temperature coefficient (VTC) is a measure of how the voltage output of a solar cell changes with temperature. It is typically expressed as the percentage change in voltage per degree Celsius (°C) of temperature change. In general, the VTCs of monofacial and bifacial cells are similar, with both types of cells exhibiting a negative VTC; thus, as temperature increases, the voltage output of the cell decreases [19, 20]. We observed similar Voc levels between the monofacial cell (677.3 mV) and bifacial cell (677.4 mV, Table 1). Although the VTC was expected to be similar, we found that the exact VTC for monofacial and bifacial cells may differ due to differences in their rear design (Figures 1(b) and 7) and dielectric structure. The VTC value (−0.46%/°C) of the type B module was greater than that of the type A module (−0.41%/°C), with a strong negative correlation between module temperature and normalized voltage. For example, VTC can be affected by the additional IR light absorption and energy generation afforded by the second surface of the bifacial cells. The EQE spectrum on the rear side in Figure 2 shows a large increase in the IR wavelength range. The monofacial cell cannot receive IR radiation because of the aluminum pastes (Figure 1(a)). Additionally, the VTC can be affected by the rear metal design and aluminum quantity, which affects bifaciality and IR quantity absorption from the rear. The rear white EVA and backsheets also have some transmittance in the IR range, which is consistent with the bifaciality results in Table 1 and the findings of previous studies [9, 21]. For these reasons, the type B module showed a relatively large VTC and different temperature properties, although

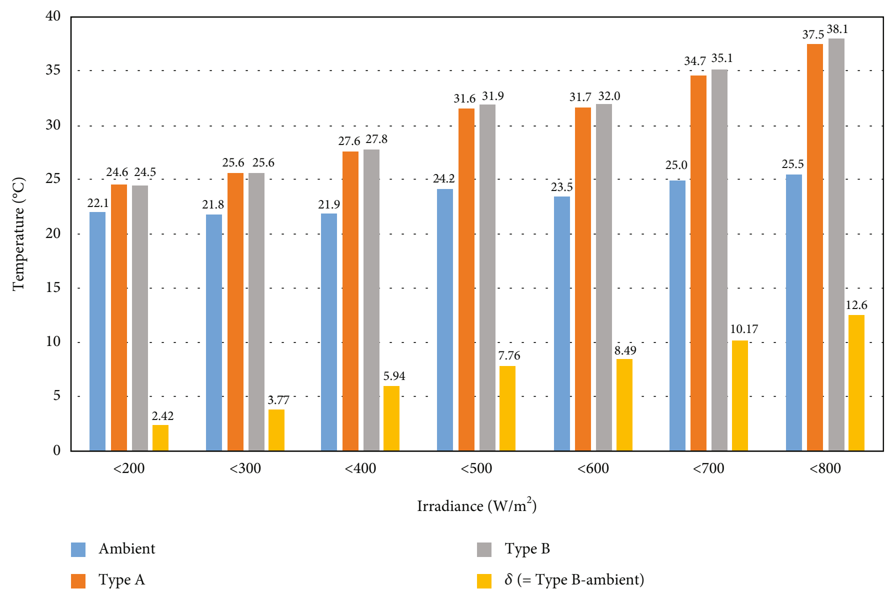


Figure 5: Temperature comparison among ambient, type A, type B, and delta between type B and ambient based on the level of irradiance. The data represent the average for each level of irradiance.

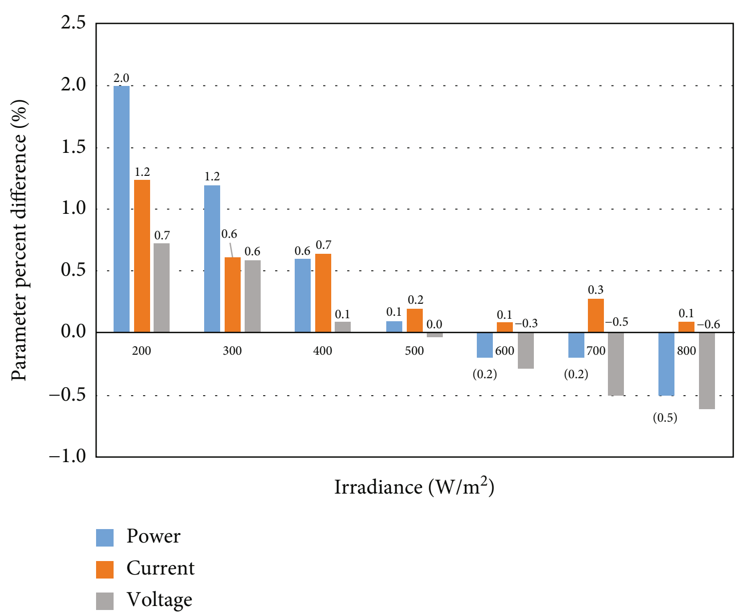


Figure 6: Module parameter (module power, current, and voltage) percentage difference with respect to the level of irradiance.

the temperature on the rear side of the module was comparable between types.

Note that the temperature measured on the backsheet did not represent the actual cell temperature [10]. Unlike the findings of our study, a previous study on module temperatures compared a monofacial cell with a back surface field-type cell and passivated emitter rear totally diffused (PERT) cell and showed that the monofacial module with the back surface field-type cell had a relatively high temperature. This is probably due to the different rear side structures with dielectric layers and metal properties and the association between design and absorption in the IR wavelength [22].

The type B module also showed better low-light performance (<500 W/m^2, Figure 6). Low-light performance is largely affected by three key parameters: shunt resistance, series resistance, and ideality factor [23]. In this study, the solar cell processes were identical on the front, so the effects of shunt resistance and the ideality factor would be comparable between types A and B. As shown in Figure 1, only the series resistance differed because of the rear side metal design. Electrical parameters, such as the FF (Table 1), also explain this difference.

Figure 8 shows the results of a simulation performed using a 2-diode model [24] to assess low-light performance

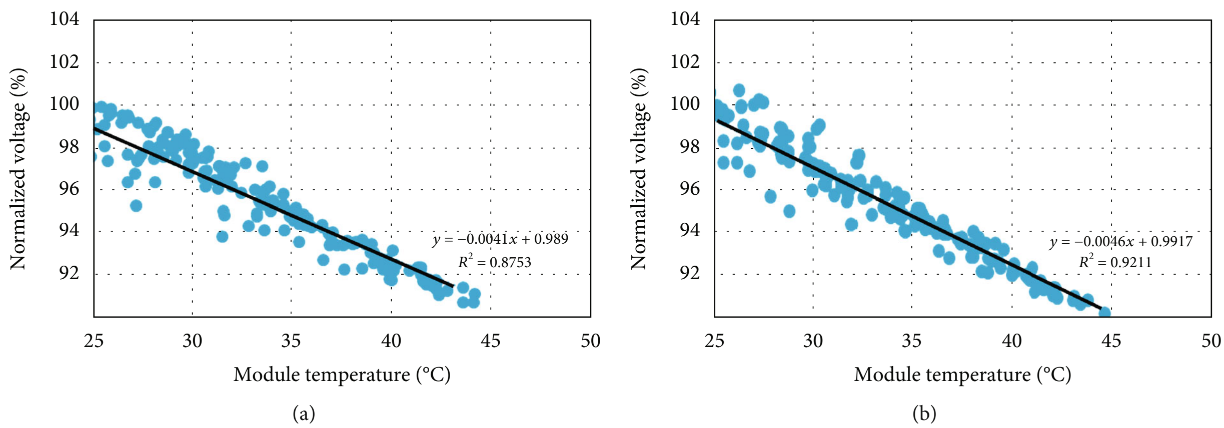


Figure 7: Voltage temperature coefficient for (a) type A module and (b) type B module. Refer also to the results in Figure 5.

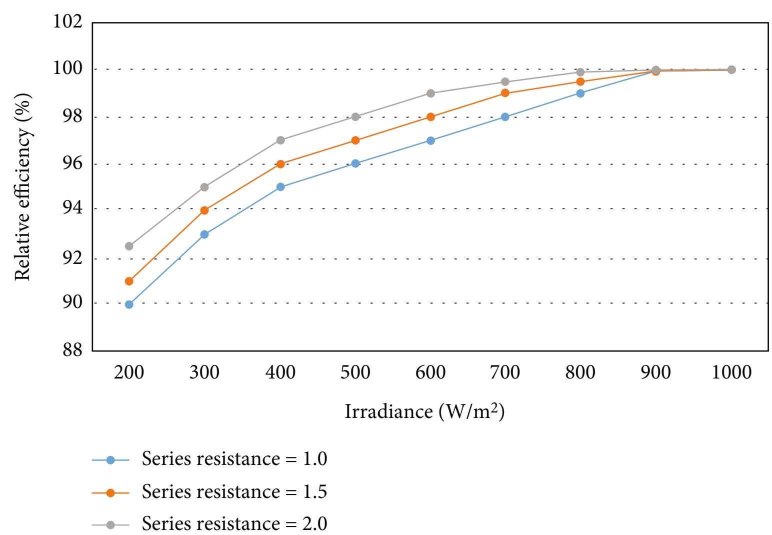


Figure 8: Simulation of relative efficiency at various levels of series resistance and irradiance.

at various levels of series resistance. The high series resistances showed improved performance during low light because the resistive losses are proportional to the current squared; however, power is only proportional to current. Therefore, the losses decreased rapidly with increasing relative efficiency (Figure 8). Similar field data were reported for a bifacial PERC module installed at a carport system [25, 26].

In summary, three effects (i.e., bifaciality, VTC, and low-light performance) can explain the electrical parameter trend shown in Figure 6. VTC and low-light performance affect each other during periods of low light, whereas bifaciality exerts an influence over the entire irradiance range.

4. Conclusions

This study investigated the performance of monofacial PV modules incorporating monofacial cells (type A, reference) or bifacial cells (type B, test) and installed at carports in Korea. The level of accumulated power over 1 month was comparable between the two types; however, each electrical parameter showed a different trend with varying irradiance and temperature. Under low-light conditions (<500 W/m^2), type B showed better performance with high voltage and current. Only the current of the type B cell showed a high value for all levels of irradiance. This variation between cells is likely explained by the bifaciality, VTC effect, and low-light performance with high resistance in the bifacial cell. This type of combined product (monofacial module with bifacial cells) may perform better under certain weather conditions, such as the low light and temperature conditions of northern European countries. The use of type B/bifacial cells can reduce production costs and achieve an LCOE with optimal energy yields if appropriate areas are selected for installation.

Data Availability

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

Acknowledgments

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