Process Integration and Optimization for Sustainability
https://doi.org/10.1007/s41660-024-00408-4

ORIGINAL RESEARCH PAPER

Comparative Study on Energy Yield of Tunnel Oxide Passivated Contact (TOPCon) and Passivated Emitter and Rear Contact (PERC) Solar Cells and Analysis of Optimal Installation Method for Vertical Photovoltaics

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Received: 25 October 2023 / Revised: 26 March 2024 / Accepted: 27 March 2024

Abstract

Photovoltaic (PV) installations have traditionally relied on a conventional south-facing orientation, which maximizes energy production at noon but has lower energy generation in the morning and afternoon. Vertical photovoltaic (VPV) systems have emerged as promising alternatives to address this inconsistency. Vertical photovoltaic systems can enhance energy generation by facing east in the morning and west in the afternoon. We compared the performance of n-tunnel oxide passivated contact (n-TOPCon) and p-passivated emitter and rear contact (p-PERC) cells in vertical photovoltaic systems to determine whether the optimal installation direction of bifacial vertical photovoltaics is east or west. Our findings indicated that n-TOPCon cells exhibited higher energy yields than p-PERC cells, with a difference of approximately 8%, attributed to the superior bifaciality and lower temperature coefficient of power of n-TOPCon. Additionally, the energy yield was higher for n-TOPCon modules when the front faced east, whereas the PERC modules performed better with a west-facing front. This contributes to the knowledge of the factors for energy production in vertical photovoltaic systems and the optimization of installation configurations.

Keywords Vertical photovoltaics · Building integrated photovoltaics (BIPV) · Net zero energy building (NZEB) energy yield · Rooftop · Korean climate · n-TOPCon · p-PERC

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Introduction

A photovoltaic (PV) system, also known as a solar power system, is a technology that converts sunlight into electricity using solar panels. PVs are increasingly used because fossil fuels are perceived to contribute to global warming through global greenhouse gas emissions. In 2021, the global capacity of PV systems was estimated to be approximately 200 GW and is still rising (Jäger-Waldau 2022). This growth has been accompanied by a remarkable decrease in the cost of commercial PV modules over the past decade. In 2011, the cost was approximately 1.7 USD per watt; however, by 2020, it plunged to just 0.2 USD per watt, marking an impressive 88% reduction in module costs (IEA 2020). PV systems are highly attractive for electricity production, potentially replacing fossil fuel–based technology. Also, interest in nearly zero-energy buildings (NZEBs) has recently been increasing for a zero-carbon society. Energy consumed in buildings is a key contributor to total energy consumption, highlighting the need of NZEBs (D'Agostino and Mazzarella 2019). For NZEBs, various energy sources can be considered, but building integrated photovoltaics (BIPV) and PV installed on rooftops are considered the most efficient and feasible methods (Gholami et al. 2021).

The PV system is a comprehensive installation system of a solar panel, and the energy output varies depending on how it is installed (Hernández-Callejo et al. 2019). Therefore, appropriate installation methods should be applied according to the situation. Recently, the photovoltaic market trend is changing from a monofacial module to a bifacial module in which the rear side also develops. According to a paper, it was reported that under rooftop conditions, the bifacial module may achieve an energy gain of about 20% or more compared to that of the monofacial module (Ernst et al., 2024). Because a bifacial module is influenced by its surroundings, albedo is an important factor. The energy yield of the bifacial module varies depending on what material the ground is made of, and thus, the LCOE (leveled cost of electricity) changes (Alam et al. 2023). If the bifacial module is installed vertically, the effect of energy yield increase due to albedo can be obtained even more. Also, vertical PV (VPV) can be utilized in various ways, such as agrivoltaics and BIPV (Garrod and Ghosh 2023).

A conventional PV system is installed by tilting by latitude in a south-facing orientation. However, conventional PV systems have an important limitation on intermittency. Conventional south-facing PV systems produce most of their energy around noon when the sunlight is the most intense, while generating less energy in the morning and afternoon (Albadi 2016). This mismatch between peak solar energy production time and peak demand time is a challenge for efficient solar energy management (Muenzel et al. 2015). East–west facing vertical PV (VPV) can be a good solution for dispersed energy production when used with conventional PVs. VPVs oriented in an east–west direction can generate the most energy in the morning and afternoon, effectively solving intermittent energy supply issues.

VPV can also be used for a variety of purposes, especially if it can be used as BIPV, and in this case, its utility can be even greater if it is combined with a PVT (photovoltaic-thermal) system. PVT is a system that produces both electricity and heat at the same time and is particularly useful for buildings that require heat. It is reported that the use of PVT can help increase the efficiency of PV by lowering the temperature of the module as well as heat production (Sourav et al. 2020; Diwania et al. 2021). Therefore, if VPV and PVT are combined and optimized, the overall system efficiency can be increased, which can be advantageous in achieving ZEB.

We particularly conducted energy measurements on a building rooftop in Seoul, Korea, which is an excellent space in deploying VPV systems. Rooftop PV systems were promoted in Hong Kong, where there is a problem with limited area, similar with Korea (Peng and Lu 2013). Rooftop PV installations could generate up to 14.2% of the total electricity production in Hong Kong, which is an indicator of its viability, value, and importance in other densely populated areas. In addition, many studies on VPV have recently been conducted in various countries. In Germany, as a result of the simulation, it was reported that when VPV was installed in the east–west direction, the energy yield was only 2% different from that of conventional tilting system (Reker et al. 2022). In the Arctic, east–west-facing VPV has higher energy yield than monofacial south-facing PV, and the energy yield increase of the bifacial module by snow has also been reported (Pike et al. 2021). There is also a study comparing modules installed vertically and horizontally (Rucker and Birnie 2023). A research was also conducted to compare VPV and single-axis tracker systems from the LCOE perspective and crop production perspective (Willockx et al. 2023). In VPV application, energy yield according to the installation method of noise barrier photovoltaics was also analyzed (Soares and Wang 2023). As such, many studies are being conducted recently in relation to VPV. Studies related with VPV are summarized in Table 1.

We conducted a comparative analysis of energy yields of the bifacial n-tunnel oxide passivated contact (n-TOPCon) and p-passivated emitter and rear contact (p-PERC) solar cells for VPV in Korean building rooftop locations. For accurate energy yield analysis, we conducted evaluations like light I-V (LIV) and external quantum efficiency (EQE)

Table 1 Recently published VPV papers

Paper	Year	Aim	Country	Analysis method
Reker et al	2022	Energy yield comparison between VPV and conventional PV	Germany	Simulation
Pike et al	2021	Field test of VPV and conventional south-facing PV	USA (Alaska)	Field test
Rucker et al	2023	Energy yield analysis by installation direction (width and length) of VPV	USA (New Jersey)	Simulation
Willockx et al	2023	Comparison of VPV and tracker system in agricultural PV	Belgium	Field test
Soares and Wang	2023	Energy yield analysis of noise barrier PV by various installation methods	USA	Simulation

at the cell level. We also fabricated a single-cell module and conducted energy yield measurements while excluding external elements.

Currently, p-PERC holds the largest market share in the PV industry. n-TOPCon is considered a highly efficient solar cell with a potential as a next-generation technology (International technology road map for photovoltaic (ITRPV), 2023). These two cell types have distinct cell characteristics, resulting in different energy yield productions. This structural difference notably impacts bifaciality. Bifaciality in PV refers to the ratio or percentage of the rear side's efficiency compared to the front side of a solar module. The rear side design must be optimized to increase bifaciality. A bifacial solar cell has a fractional metal design in the rear side to produce energy from both front and rear sides (Sepeai 2013). Bifaciality plays a critical role during energy production in VPV systems because both front and rear sides contribute equally for energy production. We included the temperature coefficient as a parameter for the analysis, as temperature affects energy production. n-TOPCon and p-PERC have different temperature coefficients (Le et al. 2020). Hence, we compared the energy performance of n-TOPCon and p-PERC solar cells in VPV systems.

In addition, we analyzed the optimal installation direction for east- and west-facing VPV systems. The morning and afternoon exhibited distinct conditions, including variations in temperature and irradiance. Therefore, it was crucial to determine the appropriate orientation of the front side. The cell characteristics and energy yield data were comprehensively investigated and analyzed to identify the optimal installation direction for the front side of the bifacial modules to maximize energy production, determine the ideal installation direction using insights gained from cell characteristic analysis and energy yield data, and offer practical recommendations for maximizing the energy yield of east- and west-facing VPV systems.

Experimental Materials

Comparison Between n-TOPCon and p-PERC

Types of samples were used: 12 busbars with M6 (16.6 × 16.6 cm) size bifacial n-TOPCon and 12 busbars with M4 (16.17 × 16.17 cm) size bifacial p-PERC. These samples have distinct structures on the front and rear sides, as illustrated in Fig. 1. For accurate energy yields, we conducted LIV measurements to measure the cell parameters. Table 2 provides cell power and bifaciality information of n-TOPCon and p-n-TOPCon and p-PERC.

The significant features of n-TOPCon cells are the n-type wafer-based cells and the presence of thin SiO_2

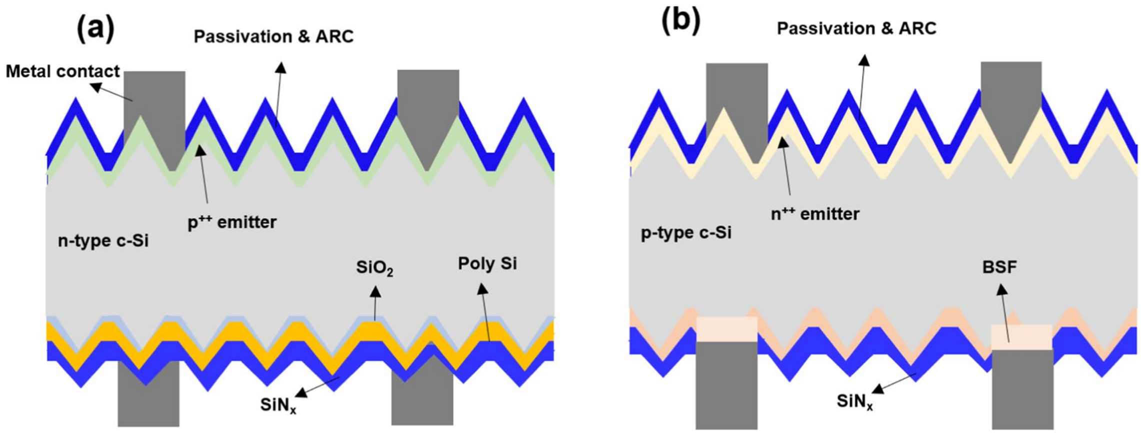

Fig. 1 Cell structure of **a** n-TOPCon and **b** p-PERC

Table 2 LIV parameters of n-TOPCon and p-PERC

	P_{max} front (W)	P_{max} rear (W)	Bifaciality
n-TOPCon	6.253	5.121	81.90
p-PERC	6.008	4.452	74.10

layer (< 1.5 nm) on the rear side, which provide passivation and tunneling effects (Yousuf et al. 2021). This layer passivates the dangling bonds and allows free electrons to penetrate (Mandal et al. 2020). Additionally, an n^+-doped poly-Si layer with a thickness ranging from 100 to 150 nm served as the back-surface field (BSF). By contrast, p-PERC utilizes an Al_2O_3 layer on the rear side for chemical and field-effect passivations owing to their negative fixed charge of approximately $10^{12}/cm^3$ (Xia et al. 2013). These structural differences contributed to variations in the rear metal fractions, with n-TOPCon cells having a lower fraction (9.5%) than p-PERC cells (20.8%). In general, p-PERC is known to have a higher metal fraction than n-TOPCon due to the rear reflection effect of Al, laser opening process, and soldering effect. TOPCon and PERC have other rear cell designs in addition to metal fraction. The rear side of the bifacial cell is designed to reduce reflection, and the rear efficiency of n-TOPCon and PERC may vary according to this design (Hwang et al. 2023). Moreover, n-TOPCon cells, which are made of n-type wafers, have longer carrier lifetimes and superior passivation capabilities than p-PERC cells (Feldmann et al. 2014). These characteristics contributed to the observed differences in the bifaciality between n-TOPCon (81.9%) and p-PERC (74.1%). These findings were supported by the EQE results, with n-TOPCon cells demonstrating a higher quantum efficiency in the wavelength range of 500 – 1000 nm, where high absorption occurs (Fig. 2a). When changing EQE to photon flux, it can be confirmed that n-TOPCon's photon flux is higher than that in the p-PERC (Fig. 2b). A similar EQE pattern of n-TOPCon and p-PERC was reported previously (Messmer et al. 2019).

When PV systems are installed in outdoor fields, the operating temperature can reach as high as 90 °C (Kurtz et al. 2011). The temperature coefficient of a Si solar cell depends on its structure and quality (Green 2003). When the temperature increases, the bandgap of the material decreases, resulting in a higher J_{sc} but a lower V_{oc}, FF. The V_{oc} drop effect was more critical than the increase in J_{sc} (Dupré et al. 2015). A previous research indicated that when irradiance is fixed, the power decreases depending on the module temperature (Sauer et al. 2014). Thus, an increase in the temperature causes a power drop when installed in the field. n-TOPCon and p-PERC are differently affected by temperature differences. TOPCon is known to have a power temperature coefficient of – 0.28/°C, and PERC is about – 0.35/°C (Le et al. 2021). An investigation of power decrease due to temperature increase in a one-sun environment confirmed that the n-TOPCon had less power loss than the p-PERC (Fig. 3).

Photothermal Effect of Front and Rear Sides

When a solar cell receives and absorbs light, its temperature increases (Radziemska 2003). The front and rear surfaces of the modules exhibited different degrees of the photothermal effect, where the temperature increased in response to light. To accurately check the photothermic effect of the cell, a thermometer was installed on the module glass and the cell, respectively, to measure each temperature at one sun. The front side experienced a rapid and higher temperature increase than the rear side for both the n-TOPCon and p-PERC modules (Fig. 4a). The temperature difference

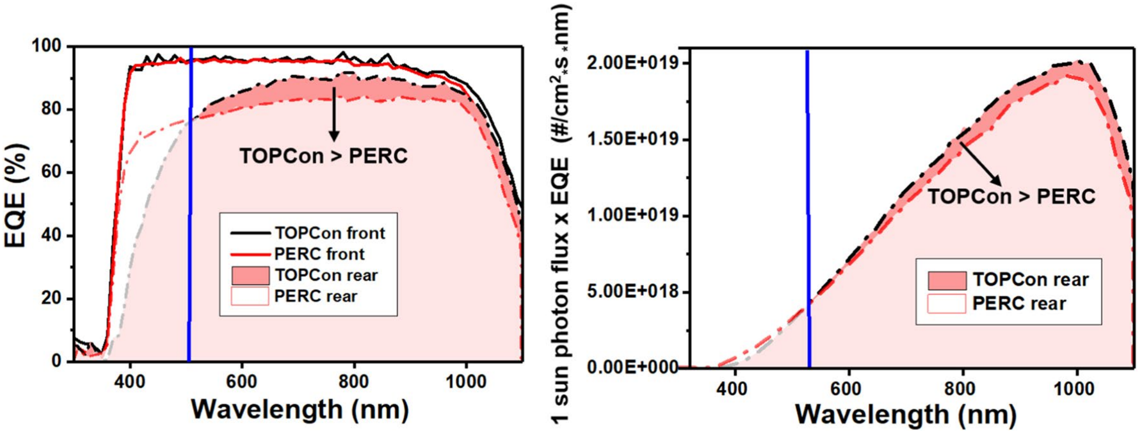

Fig. 2 **Aa** EQE of n-TOPCon and p-PERC, **b** rear-side photon flux by wavelength of n-TOPCon and p-PERC

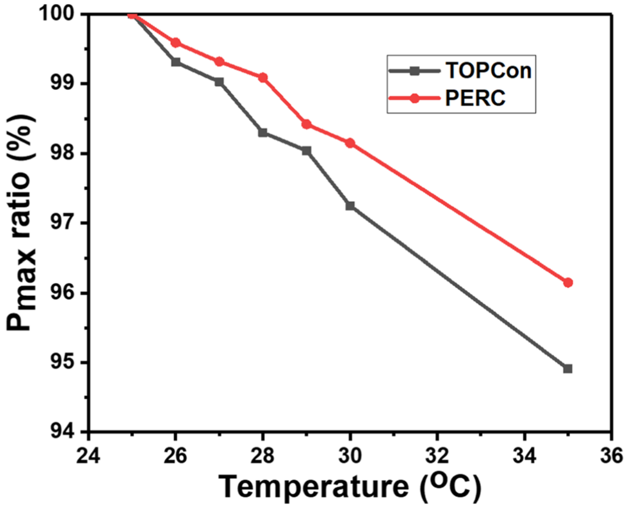

Fig. 3 $P_{\max}$ reduction ratio graph by temperature increase

between the front and rear sides was approximately 8 °C for n-TOPCon and 5 °C for p-PERC, which was primarily influenced by differences in reflectance. Figure 4b shows that both the n-TOPCon and p-PERC modules exhibit higher reflectivity on the rear surface than on the front surface. Notably, the reflectance difference was more pronounced in the n-TOPCon, which aligns with its tendency to experience a higher temperature increase under one-sun illumination. As the afternoon progressed and temperatures rose, the energy yield difference between the east and west samples diminished, owing to the reduced degradation on the rear surface caused by the photothermal effect.

Experimental Method

Module Structures

The modules used in this study were fabricated using a single cell, and the module components consisted of an ethylene vinyl acetate (EVA) sheet and a 3.2-mm glass. The module size was 20 × 20 cm, which provided a suitable size for the measurements. To perform measurements on defect-free samples, visually clear samples were identified using electroluminescence (EL) images.

Vertical PV System

To assess the energy yield of the VPV system, an outdoor field test was conducted over a 1-month period in April at Seoul (latitude of 37.5°, longitude of 127°) because it displays distinct seasons. The system was installed on the rooftop to ensure unused space and minimize shading from the surrounding obstacles. To ensure accurate alignment, a compass was used to orient the frames precisely southward, and the tilting angle was set at 90°. The experimental setup consisted of four channels, with each sample (n-TOPCon and p-PERC) installed in an east/west configuration (Fig. 5).

The east sample has the front of the bifacial module facing east, and the west sample has its front facing west. The east sample was positioned on the left, and the west sample was placed on the right, enabling a direct comparison under identical environmental conditions. Throughout the field test, the I-V parameters, temperature, and irradiation data were collected for each sample at intervals of 3 min.

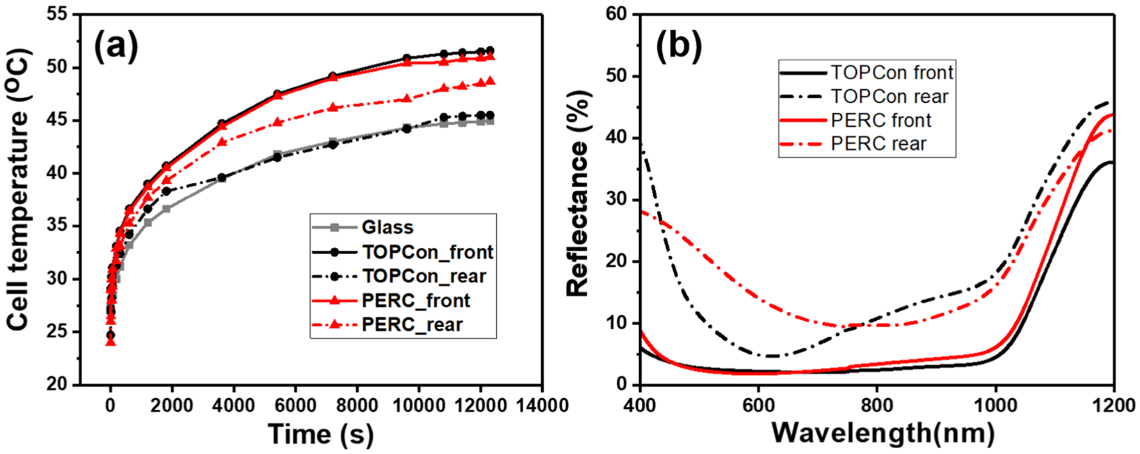

Fig. 4 **a** Temperature increase graph in one-sun illumination of n-TOPCon, p-PERC, and glass, **b** reflectance graph of n-TOPCon and p-PERC

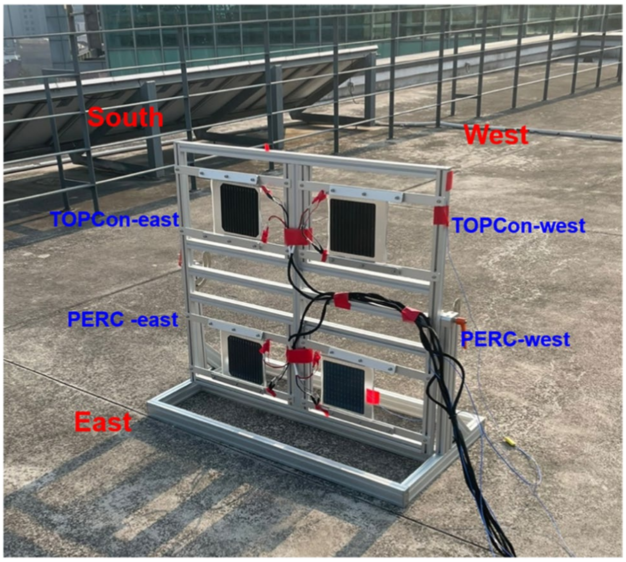

Fig. 5 Image of the vertical PV system

Results and Discussion

Comparison of Energy Yield for n-TOPCon and p-PERC

As expected, the energy yield graph exhibited two peaks in the morning and afternoon. In terms of energy yield, the n-TOPCon module outperformed p-PERC module for both the east- and west-facing samples. The graph clearly demonstrated a significant difference in the energy yield between the rear sides of the eastern and western samples (Fig. 6a, b). When combining the energy yield of the east and west samples, n-TOPCon achieved a higher energy yield of 44.24 Wh/Wp compared to p-PERC's 41.12 Wh/Wp during the measurement period (March 29 ~ May 1 2023), which resulted in a higher energy production throughout the day (Fig. 6c). This difference can be attributed to the higher bifaciality and lower temperature coefficient of n-TOPCon. The magnitude of energy yield difference varied depending on the

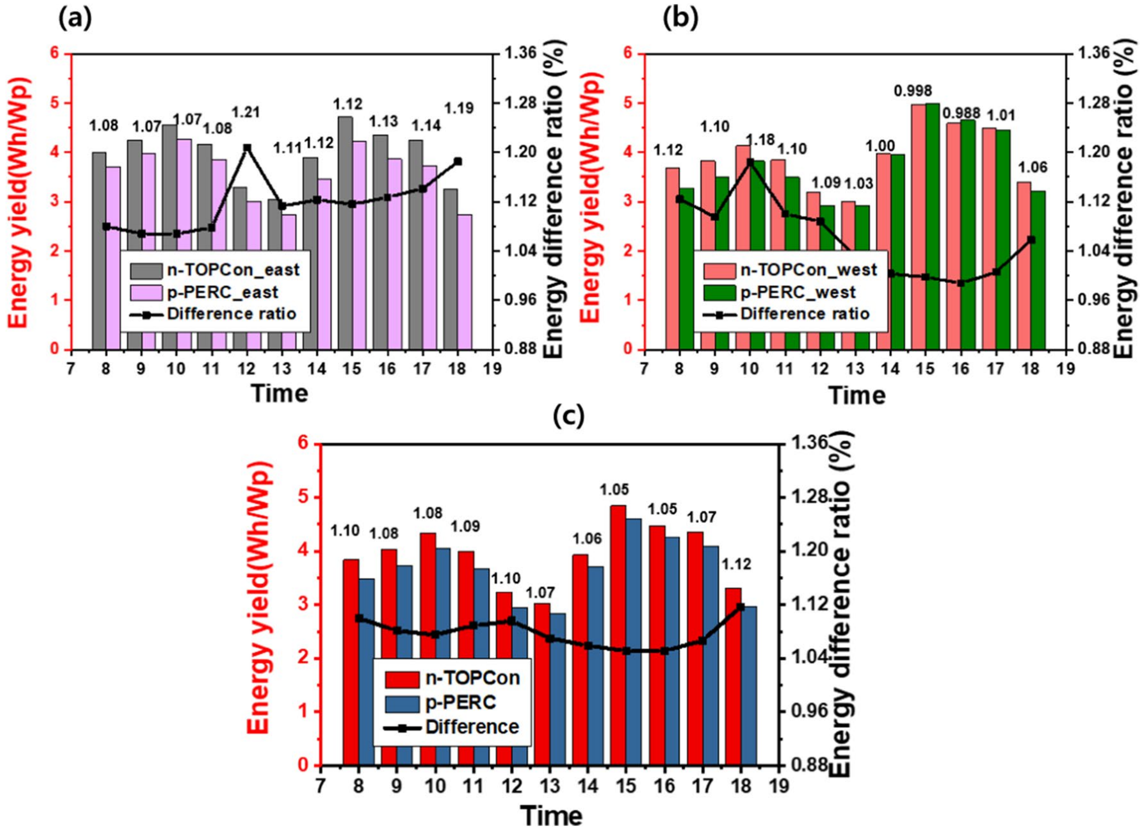

Fig. 6 Energy yield graph of n-TOPCon and p-PERC. **a** Energy yield graph of east samples, **b** energy yield graph of west samples, **c** energy yield graph of n-TOPCon and p-PERC

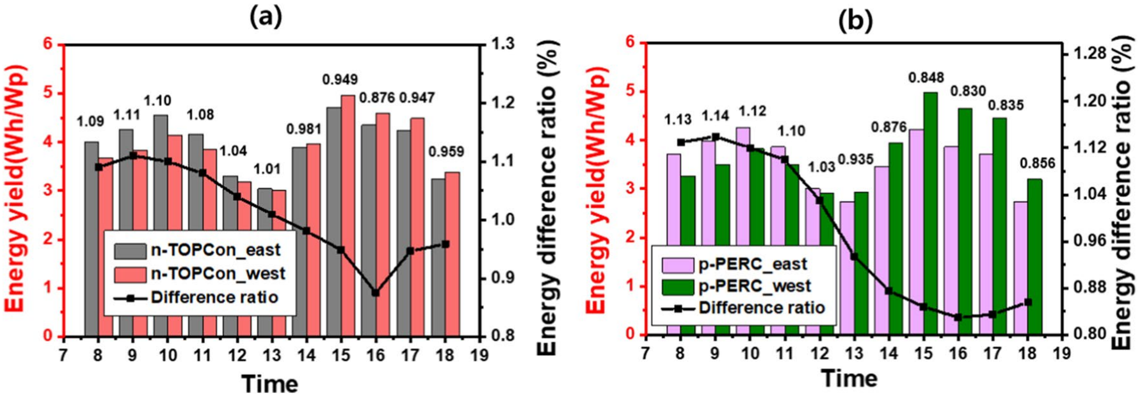

Fig. 7 **a** Energy yield graph of n-TOPCon east and west samples, **b** energy yield graph of n-PERC east and west samples

installation direction, with the east sample showing more than twice the energy yield difference compared to the west sample.

Determining Optimal Installation Direction

Figure A.4 (a) shows the morning and afternoon I_{sc} data. According to the I_{sc} data, more light reached the site in the afternoon than in the morning. In addition, in Figure A.4 (b), the energy yield was higher in the afternoon than in the morning for both cell types. To determine the optimal installation direction between east and west, the energy yields according to the direction of the n-TOPCon and p-PERC were compared. However, different trends were observed for n-TOPCon and p-PERC as shown in Fig. 7. For n-TOPCon, the east sample produced approximately 1.7% more energy, whereas the west sample produced approximately 3.7% more energy for p-PERC. This phenomenon can be explained by bifaciality and photothermal effects.

p-PERC has lower bifaciality and lower temperature difference between the front and rear sides. Therefore, bifaciality had a greater effect than the photothermal effect difference between the front and rear sides. For p-PERC, the west sample produced more energy in the front in the afternoon when irradiance and temperature were high. However, n-TOPCon has higher bifaciality and a higher temperature difference between the front and rear sides. This contributed to a different energy yield pattern between n-TOPCon than with p-PERC. A higher photothermal effect reduced the afternoon energy yield gap between the east and west samples. Thus, for n-TOPCon, the east sample produced more energy than that for west sample.

Graphical representation highlights the disparity in energy yield between the east and west samples of n-TOPCon and p-PERC during the morning and afternoon (Fig. 8). For n-TOPCon, the difference between the east and west samples was larger in the afternoon compared to that in that morning. Conversely, the p-PERC exhibited a greater energy yield disparity between the two samples during the afternoon due to its lower bifaciality.

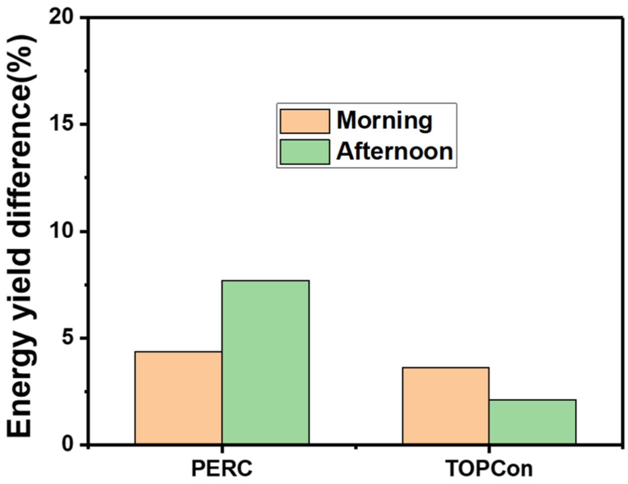

Fig. 8 Energy yield difference graph between east and west samples in the morning and afternoon

Conclusions

This study compared bifacial n-TOPCon and p-PERC to find the optimal installation methods for VPV systems at building rooftops. The total energy yield of n-TOPCon was 44.24 Wh/Wp, whereas that for p-PERC was 41.12 Wh/Wp. Crucially, the energy production of the rear side is vital for VPV systems, and n-TOPCon exhibited a higher bifaciality of approximately 8% compared to that for p-PERC, resulting in a higher energy yield. Additionally, n-TOPCon demonstrated a lower power temperature coefficient, which influenced the energy yield. The optimal installation direction differed between n-TOPCon (east) and p-PERC (west), driven by variations in bifaciality and a lower photothermal effect on the rear side. Therefore, the optimal installation direction depends on the cell characteristics. Previous studies on VPV have emphasized the potential for VPV, but this study is meaningful because we showed that TOPCon has superior bifaciality and cell characteristics than PERC, proving that TOPCon is suitable for VPV, and also provides a solution for the installation direction. Also, the data used in this study covered only 1 month, while a year-long monitoring period will be required for the analysis of energy yield patterns. Adjusting the installation direction of the VPV system to the east or west offers the potential to adjust the energy peak times, making this an intriguing subject for future research.

Funding This work was supported by the "Human Resources Program in Energy Technology" of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and granted financial resource from the Ministry of Trade, Industry & Energy, Republic of Korea (No. 20204010600470 and No. 20213030010400).

Data Availability Data are contained within the article.

Declarations

Conflict of Interest The authors declare no competing interests.

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