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An Analysis for Performance of PERC and TOPCon Modules Under low Irradiance Level

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Abstract. In this paper, the performances of PERC and TOPCon photovoltaic (PV) modules under low irradiance levels are investigated. It is found that the specific efficiency of TOPCon module is always larger than that of PERC under low light intensities. Meanwhile, as irradiance decreases, this efficiency advantage for TOPCon module become more obvious. To explain this phenomenon, two key aspects are analyzed. First, the recombination parameters of both modules are calculated. It is found that the recombination parameter of PERC module is larger than that of TOPCon module. However, this difference become smaller with the decreasing irradiance. In addition, the series resistance (R_s) and shunt resistance (R_{sh}) of both modules, along with the rates of efficiencies change with respect to these resistances, are investigated. It is found that PERC modules exhibit higher R_s and R_{sh}, while the rates of efficiency change with respect to R_s and R_{sh} for PERC are lower, compared to TOPCon module. Moreover, as the irradiation decreases, the R_s of PERC increases significantly, and the rate of efficiency change with respect to shunt resistance for TOPCon module is decreased more obviously than that of PERC module. Although we have found the module efficiency is more sensitive to changes in R_{sh} but less sensitive to R_s, the high series resistance disadvantage and high shunt resistance advantage for PERC module are amplified and suppressed, respectively. These above results provide new insights for the investigation and development of PV modules.

Keywords: Efficiency, Recombination, Series Resistance, Shunt Resistance

1. Introduction

The performance of photovoltaic (PV) modules is typically characterized under standard test conditions (STC), as specified by IEC 60891 and IEC 61836[1-2]. However, the real operating environment for PV modules is often far more variable. In regions with insufficient solar irradiance, such as high-latitude areas, some types of PV modules suffer significant performance losses, leading to significant economic losses. Therefore, it is important to study and compare the performance of different types of PV modules under low irradiance levels.

Several studies have explored the PV modules performance under varying irradiance. A. Kassis et al. examined the electrical characteristics of several polycrystalline silicon solar cells under low irradiance [3]. N.H. Reich et al. analyzed the I-V characteristics of monocrystalline and polycrystalline silicon solar cells from eight manufacturers over an irradiance range of 3 to 1000 W/m² [4]. M. Chegaar et al. investigated the variation of multiple electrical parameters of polycrystalline silicon solar cells with irradiance [5].

Although these studies have investigated the performance of various types of PV modules under different irradiance levels, none explore the combined effects of the resistive losses and the recombination of the module to explain the performance variations of different types of PV modules under varying light intensities. These factors are crucial for understanding the adaptability and improvement of PV modules in diverse geographical environments. In this paper, the performance of TOPCon and PERC module is investigated. It is found that the TOPCon module maintain superior stability and performance under decreasing irradiance compared to PERC modules. Meanwhile, as irradiance decreases, this efficiency advantage for TOPCon module become more obvious. To explain this observation, two aspects are analyzed. Firstly, the recombination parameters J_0 for both PV modules are calculated. It is found that the J_0 for PERC module is always larger than that of TOPCon module. However, as irradiance decreases, this difference become smaller. This is inconsistent with the above phenomenon, suggesting that there are other factors influencing the performance of modules. In addition, the series and shunt resistances of both modules are calculated and the rates of efficiencies change with respect to these resistances are analyzed. It is found that, compared to TOPCon module, the series and shunt resistances of PERC module were both larger. It has been observed that PERC modules exhibit higher series resistance (R_s) and shunt resistance (R_{sh}) compared to TOPCon modules. However, the change in efficiency with respect to R_s and R_{sh} is lower for PERC modules. Additionally, as irradiation decreases, the Rs of PERC modules increases significantly. The rate at which efficiency changes in response to R_{sh} is more pronounced for the TOPCon module than for the PERC module. Although we have found that the module efficiency is more sensitive to changes in R_{sh} but less sensitive to R_s, the high series resistance disadvantage and high shunt resistance advantage for PERC module are amplified and suppressed, respectively. The results obtained above indicates that the PERC module performance under low irradiance was limited by its recombination parameter and resistance, so that it is less suitable for regions with insufficient solar radiation compared to TOPCon modules. This paper provides new insights for improving and developing PV technologies.

2. Experimental details

In this experiment, an AAA class solar simulator (XJCM-13A) with a thermostatic chamber was used to measure the electrical performance of PERC and TOPCon photovoltaic modules under various irradiance levels and temperatures. The temperature of the modules was maintained within ±1°C of the target during the experiments. The series resistance (R_s) and shunt resistance (R_{sh}) of the modules were measured and obtained using the following equations [6]:

$$R_s = \left(\frac{dV}{dI}\right)\Big|_{V=V_{oc}} \tag{1}$$

$$R_{sh} = \left(\frac{dV}{dI}\right)\Big|_{I=I_{sc}} \tag{2}$$

R_s and R_{sh} were derived from the slopes of the I-V curve near the short-circuit current and open-circuit voltage, respectively. Therefore, as long as the I-V curve can be measured, the corresponding resistance can be obtained.

3. Results and discussion

The electrical characteristics of the PV modules were modeled using the single-diode equation:

$$I = I_{ph} - I_0 \times [Exp(\frac{V+IR_s}{nkT/q}) - 1] - \frac{V+IR_s}{R_{sh}} \tag{3}$$

Where I_{ph} is the photocurrent, I_0 is the recombination parameter, n is the ideality factor, k is Boltzmann constant, q is the electron charge. Given that the exponential term is much larger than 1, the recombination current I_0 was extracted by rearranging the equation:

$$I_0 = \frac{I_{ph}R_{sh} - V - IR_{sh}}{R_{sh}Exp(\frac{V+IR_s}{nkT/q})} \tag{4}$$

In addition, based on the single-diode equation and the Lamber W function [7], the current and voltage at maximum power points (MPPs) can be expressed in the following form:

$$I_{mpp} \approx I_{\text{ph}} \times \left(1 - \frac{1}{\omega}\right) - \frac{1}{R_{\text{sh}}} \times \frac{nk(\omega - 1)}{q} \times T \tag{5}$$

$$V_{\text{mpp}} \approx -R_{\text{sh}} \times I_{\text{ph}} \times \left(1 - \frac{1}{\omega}\right) + \frac{R_{\text{s}} + R_{\text{sh}}}{R_{\text{sh}}} \times \frac{nk(\omega - 1)}{q} \times T \tag{6}$$

Here, $\omega = W\{I_{\text{ph}}q / I_0\}$. Subsequently, by combining the definition of efficiency and equations (5) and (6), the rate of efficiency change with respect to series and shunt resistance was derived as follows:

$$\frac{d\eta}{dR_s} = \frac{I_{mpp}}{SGR_{sh}} \times \frac{nk(\omega-1)T}{q} \tag{7}$$

$$\frac{d\eta}{dR_{sh}} = \frac{V_{mpp}}{SGR_{sh}^2} \times \frac{nk(\omega-1)T}{q} - \frac{I_{mpp}}{SG}\left[I_{ph}(1-\omega/1) + \frac{R_s}{R_{sh}^2} \times \frac{nk(\omega-1)T}{q}\right] \tag{8}$$

Where S is the area of the module and G is the irradiance. The specific efficiency and recombination parameter are defined as:

$$Specific\,efficiency = \frac{\eta(G,T)}{\eta_{STC}} \tag{9}$$

$$Specific\,recombination\,parameter = \frac{J_0(G,T)}{J_{0,STC}} \tag{10}$$

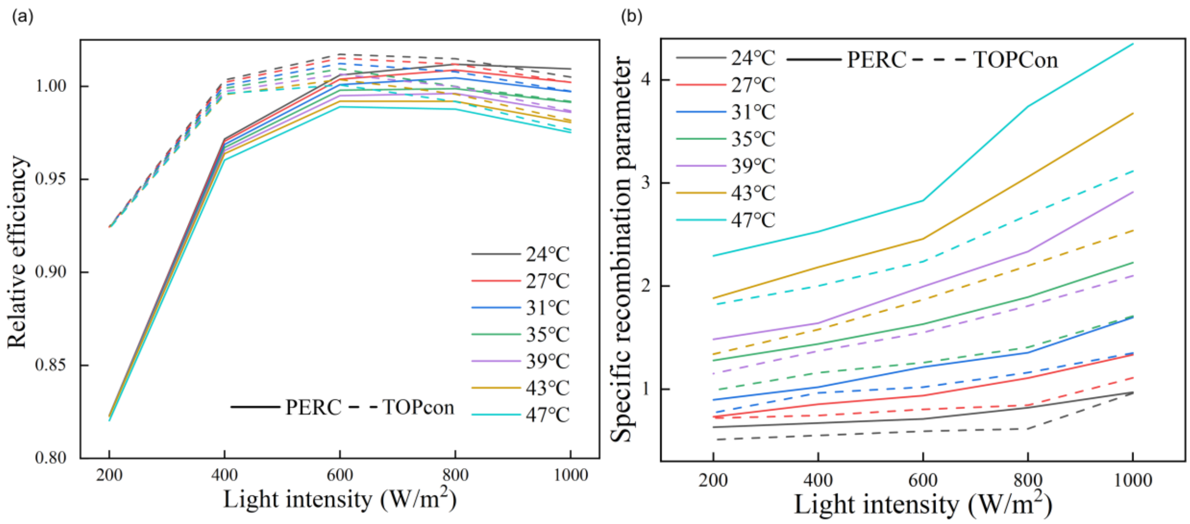

Figure 1. *(a) The specific efficiency and (b) recombination parameters of PERC and TOPCon modules at different light intensity and temperature*

Figure 1 (a) shows the specific efficiencies of PERC and TOPCon modules under varying irradiance and temperature conditions. It can be found that, as irradiance decreases, the PERC module shows a more significant decline in specific efficiency compared to the TOPCon module. Figure (b) illustrates the specific recombination parameters of both modules under different conditions. It is found that, as irradiance decreases, the recombination parameters of both modules decrease. However, the reduction in recombination parameter is more pronounced for PERC module than for TOPCon module under decreasing irradiance. From a surface perspective, this phenomenon may be attributed to the differences in surface passivation schemes employed in the two technologies. As reported in [8], surface passivation quality plays a crucial role in determining the recombination behavior, especially under low-irradiance conditions where surface recombination becomes a dominant loss mechanism. The PERC module typically utilizes an Al_2O_3/SiN_x passivation stack, which, although effective, may exhibit greater sensitivity to irradiance-dependent carrier concentration, leading to a more significant increase in recombination at lower light levels. In contrast, TOPCon structures employ a tunnel oxide layer and polycrystalline silicon (poly-Si) layer that form a highly effective passivated contact, maintaining lower surface recombination velocities even under reduced irradiance. Structurally, the intrinsic differences in the internal cell design also play a pivotal role. As outlined in [9], the presence of full-area rear passivated contacts and reduced metal-induced recombination in TOPCon cells contributes to a more stable recombination profile over varying irradiance and temperature conditions. On the other hand, for PERC cells, the use of localized rear contacts introduces regions without passivation, which are prone to rear-surface recombination. Moreover, if the rear passivation layer is too thin, its ability to reduce interface defects and provide field-effect passivation is weakened, further increasing recombination losses.

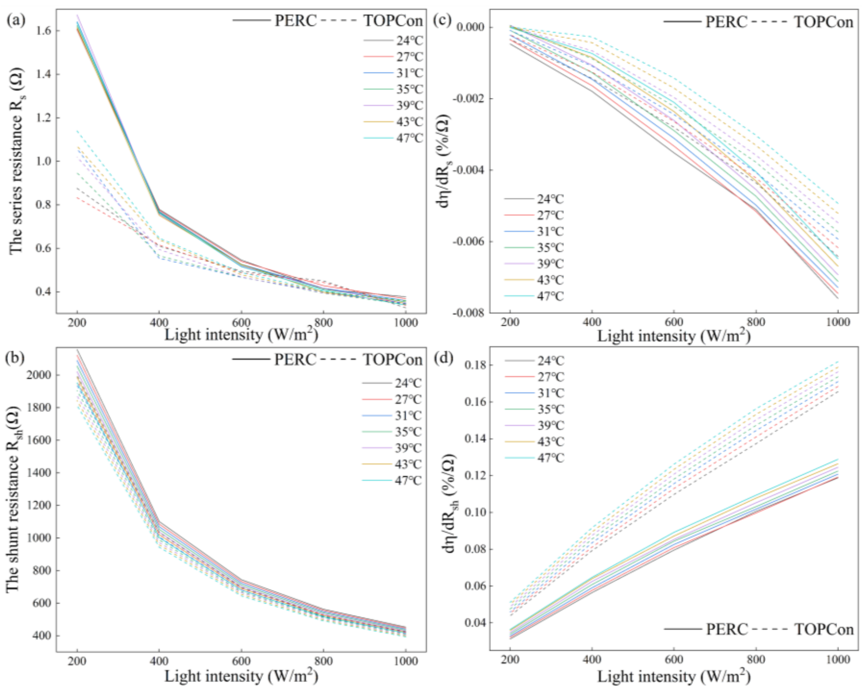

Figure 2. *(a) The series resistance R_s and (b) the shunt resistance R_{sh} of PERC and TOPCon modules under varying conditions; Rates of efficiency change with respect to (c) series resistance R_s and (d) shunt resistance R_{sh} for PERC and TOPCon modules under different conditions*

Figure 2 (a) and (b) shows the R_s and R_{sh} of PERC and TOPCon modules under different irradiance and temperature conditions. It is found that both R_s and R_{sh} are larger for PERC module than for TOPCon module. The higher R_s can reduce the performance of PERC module, while the larger R_{sh} can improve the performance. Figure 2 (c) and (d) presents the rate of efficiency change with respect to R_s and R_{sh} for both modules. It is evident that PERC module exhibit lower rate of efficiency change with respect to both R_s and R_{sh} compared to TOPCon modules. The efficiency change rate with R_s is negative, while with R_{sh} it is positive. As shown in Figure 2 (a) and (b), both modules exhibit increasing R_s and R_{sh} as irradiance decreases, with R_s showing more significant shifts. Additionally, Figure 2 (c) and (d) reveals that the efficiency changes rates for R_s and R_{sh} differ between the two modules. It can be found that the efficiency change rate with R_{sh} converges as irradiance decreases, while the rate with R_s remains nearly parallel. In addition, although the Figure (c) and (d) have illustrated the module efficiency is more sensitive to changes in R_{sh} but less sensitive to R_s, the high series resistance and recombination parameter disadvantage and high shunt resistance advantage for PERC module are amplified by the e exponential term in equation (3) and suppressed by the efficiency change rate, respectively.

4. Conclusions

In this paper, the performance of different photovoltaic (PV) modules under varying irradiance levels were compared, which helps optimize module selection and reduce financial losses for system owners. Understanding the factors contributing to poor performance under low irradiance is crucial for the development and improvement of PV technologies. This study demonstrates that TOPCon modules outperform PERC modules under low irradiance, driven by two main factors. First, PERC modules exhibit higher recombination under low irradiance, which limits their performance. Second, PERC modules have larger series resistance, which further suppresses their efficiency as irradiance decreases. Although PERC modules have higher shunt resistance, the efficiency gain expected from this is reduced by the reduction in irradiance. Specifically, the high series resistance and recombination parameter disadvantage and high shunt resistance advantage for PERC module are amplified and suppressed, respectively. In conclusion, the findings of this study not only provide guidance for selecting appropriate PV modules in regions with low solar irradiance but also offer insights for the future development and optimization of PV technologies.

Data availability statement

The data presented in this study are available on request from the corresponding author.

Author contributions

Conceptualization: Baojie Lv and Hong Yang; Methodology: Baojie Lv and Hong Yang; Validation: Baojie Lv; Formal Analysis: Baojie Lv; Resources: Hong Yang; Data Curation: Baojie Lv; Writing – Original Draft Preparation: Baojie Lv; Writing – Review & Editing: Xixiang Xu, Mingzhe Yu, Wenan Tie, Wangchun Xi; Visualization: Baojie Lv; Supervision: Hong Yang; Project Administration: Hong Yang; Funding Acquisition: Hong Yang.

Competing interests

The authors declare no conflict of interest.

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