EXPERIMENTAL OBSERVATIONS ABOUT THE CLOUD ENHANCEMENT PHENOMENON ON PV STRINGS

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ABSTRACT: Due to the cloud enhancement (CE) phenomenon, irradiance on partly cloudy days can considerably exceed the expected clear sky irradiance. Although CE is a well-known phenomenon, its effects on the operation of photovoltaic (PV) power systems have not been studied comprehensively based on electrical measurements. In this paper, the characteristics of CE events are analysed based on irradiance measurements and by examining the operation of three PV strings based on current–voltage curves measured under CE conditions. The highest measured irradiances were about 1450 W/m^2 while the theoretical clear sky maximum irradiance is about 900 W/m^2. It means that the highest measured irradiance was about 1.7 times the expected clear sky irradiance. Correspondingly, the highest measured powers exceeded the highest theoretical clear sky powers. Although the measured maximum power point (MPP) powers exceeded the nominal standard test conditions MPP power, the MPP voltages were typically lower than the nominal MPP voltage. The reason for this is that during the CE events, temperature was typically much higher than in standard test conditions. The experimental results of this study show that CE events do not cause problematic increase of PV system operating voltages and confirm the findings of earlier simulation studies.
Keywords: Cloud Enhancement, Overpower, Plant Control, PV Array, Voltage Fluctuation

1 INTRODUCTION

Power production of photovoltaic (PV) generators is dependent on the irradiance incident on the PV cells of the generator. Solar radiation is highly variable due to shadings caused by moving clouds [1]. The nominal electrical values of PV modules are usually defined under the standard test conditions (STC), which are not common in practise. In many areas of the world, the global irradiance from clear sky around solar noon can be higher than the STC irradiance of 1000 W/m^2 [2]. Furthermore, on partly cloudy days, irradiance incident on the PV modules can considerably exceed theoretical clear sky irradiance as a consequence of a phenomenon called cloud enhancement (CE) [3] or overirradiance [4]. Clear sky irradiances exceeding the STC irradiance are typically not an issue, as the exceedance is less than 10% in most parts of the world and, correspondingly, PV power losses due to high module temperatures are typically greater than 10% compared to operation at the STC temperature of 25 °C. However, under CE conditions, irradiance can be much higher and PV cell temperatures can be lower leading to higher PV powers. For example, in [5], up to 30% higher power output of PV modules compared to the STC were reported.

Although CE is a well-known phenomenon [6], its effects on the operation of PV systems have been studied only in few articles: the operation of individual PV modules under CE conditions was studied in [5]; the operation of a PV plant under a single CE situation was studied in [7]; and inverter sizing and energy losses due to inverter saturation under CE conditions were studied in [8]. In [3], [9], the effects of CE on the operation of PV generators were extensively studied using operating condition measurements as inputs for simulations. However, comprehensive studies of the operation of PV generators under CE conditions based on actual electrical measurements have not been presented earlier.

In this paper, experimental observations about the CE phenomenon on PV strings are presented. Characteristics of CE events are analysed based on irradiance measurements and the operation of three PV module strings under CE conditions is studied based on measured current–voltage (*I–U*) curves of the strings. The global maximum power point (GMPP) characteristics of the strings are studied comprehensively. The GMPP characteristics of PV strings have previously been studied experimentally in [10], [11]. However, those studies were not focused on CE conditions, but instead analysed measurements of whole days. The aim of this experimental study is to investigate the effects of CE phenomenon on the operation of PV strings based on *I–U* curve measurements. The study is novel, because no such equally comprehensive studies based on actual electrical measurements have been presented earlier.

2 EXPERIMENTAL DATA AND METHODS

The experimental data consists of irradiance measurements of six summer months (June–August 2021 and 2022) and of 70 days of full-day *I–U* curve measurements from the PV research plant of Tampere University [12]. The layout of the studied PV strings, consisting of 6 (String 4), 17 (String 1) and 23 (String 1&4) series-connected PV modules, is presented in Fig. 1 and their details are compiled in Table I. The analysed measurements of String 1 (13 days) were performed on 14–19 June and 25–31 July, 2022. The measurements of String 4 (22 days) were performed on 1–2 June and 12–17 August, 2021 and on 11–17 July and 1–7 August, 2022. The measurements of String 1&4 (35 days) were performed on 3–9 June and 5–11 August, 2021 and on 27–30 June, 1–10 July and 8–14 August, 2022. Daily measurement period was from 8:00 to 18:00 (UTC+2). An *I–U* curve tracer, where IGBTs act as a variable load, was used to measure an *I–U* curve once a second. Hence, in total, 2520000 measured *I–U* curves were analysed. The irradiance incident on nine PV modules of the studied strings was measured by photodiode-based SP Lite2 pyranometers mounted at the same 45° tilt angle as the PV modules. Back-sheet temperatures of those modules were measured by Pt100 temperature sensors. Moreover, global horizontal

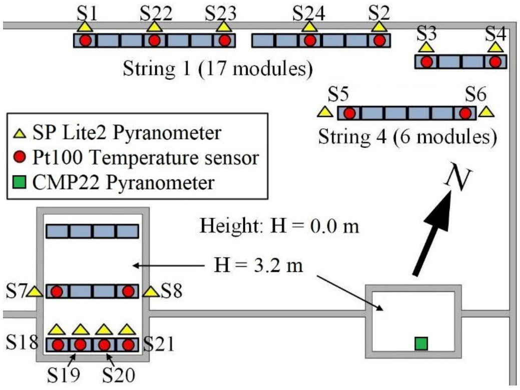

Figure 1: Partial layout scheme of the PV power research plant of Tampere University.

Table I: Details of the studied PV strings.

	String 1	String 4	String 1&4
Number of PV modules	17	6	23
$U_{\mathrm{MPP,\,STC}}$ (V)	439	155	593
$P_{\mathrm{MPP,\,STC}}$ (W)	3230	1140	4370

irradiance (GHI) was measured by a CMP22 pyranometer. All irradiance and temperature measurements were performed with a sampling frequency of 10 Hz. Locations of the irradiance and temperature sensors are presented in Fig. 1. Average irradiances and temperatures of the strings were calculated as the averages of all the sensors of the string.

Each measured *I–U* curve involves 4000 measured *I–U* value pairs. The following procedure was used to pre-process the *I–U* curves. First, the measurement points having identical voltage value were replaced with a single point by averaging their current values. After that, clearly abnormal measurement points were removed. A measurement point was removed if its power differed from the previous and following measurement point by more than 1.3 times the mean change of power between adjacent measurement points in its vicinity (previous and next 9 points). Finally, the measured current and voltage values were smoothed separately using smooth.m function in MATLAB.

A CE event is typically defined by comparing measured irradiance with expected clear sky irradiance [13, 14] or with a static irradiance limit. In that way, a CE event is defined to start when the measured irradiance exceeds the threshold and to end when the irradiance decreases below it. From the PV system operation point of view, the most reasonable choice for the static threshold is the STC irradiance. Another static threshold used is the solar constant [13, 15]. In this study, a continuous range of irradiance values starting from the STC irradiance of 1000 W/m^2 was used similarly than in [3, 16] and all events where the measured irradiance exceeded the irradiance limit were identified. That makes the obtained results more generalizable than use of a single static irradiance threshold. CE events were identified in measured powers by a similar approach using a continuous range of power values starting from the nominal STC powers (see Table I) of the strings. An overpower event starts when the measured power exceeds the threshold and ends when the power decreases below it.

3 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 CE events identified in irradiance measurements

Fig. 2 presents the shares of the studied days as a function of an irradiance limit, where the irradiance caused by the CE phenomenon for one PV module, GHI, and the strings exceeded that irradiance limit. CE events measured by sensor S24 exceeded 1000 W/m^2 in around 80% of the days and 1200 W/m^2 in around 40% of the days. CE events were more infrequent for GHI and the PV strings due to a suboptimal tilt angle and a larger land area, respectively. CE events were more infrequent for String 4 than for Strings 1 and 1&4, although String 4 is the shortest studied string, since String 4 is located closer to a nearby built structure (see Fig. 1) and thus is more frequently shaded than Strings 1 and 1&4.

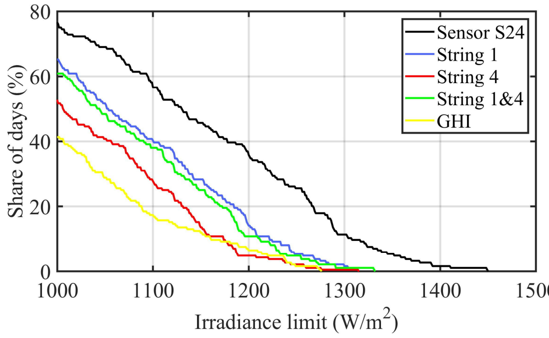

Figure 2: Shares of days with CE irradiance higher than the irradiance limit.

The numbers of identified CE events for the PV module, GHI, and the strings are presented in Fig. 3 as a function of the irradiance limit. There were about 20000 CE events for sensor S24 which exceeded 1000 W/m^2. For the PV strings the corresponding number was from 3300 to 5200. The highest irradiance measured by sensor S24 was 1449 W/m^2. It is worth noting that the highest theoretical clear sky irradiance in the Tampere region is just over 900 W/m^2. Thus, the highest measured irradiance was about 1.7 times the expected clear sky irradiance. The highest measured irradiances for the strings were over 1300 W/m^2. The highest measured irradiances are compiled in Table II.

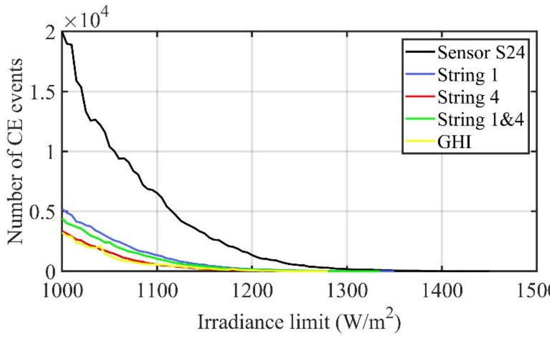

Figure 3: Numbers of CE events as a function of the irradiance limit.

Fig. 4 presents the cumulative and maximum durations of the CE events as a function of the irradiance limit. The durations decreased sharply with the increasing irradiance limit. The total durations of the CE events exceeding 1000 W/m^2 was 71 hours, i.e., 1.6% of the time,

Table II: The highest measured irradiances.

Sensor/String	Highest irradiance (W/m^2)	Day
S23	1399	July 29, 2022
S24	1449	June 4, 2022
String 1	1348	July 29, 2022
String 4	1315	June 4, 2022
String 1&4	1332	July 29, 2022
GHI	1276	July 15, 2022

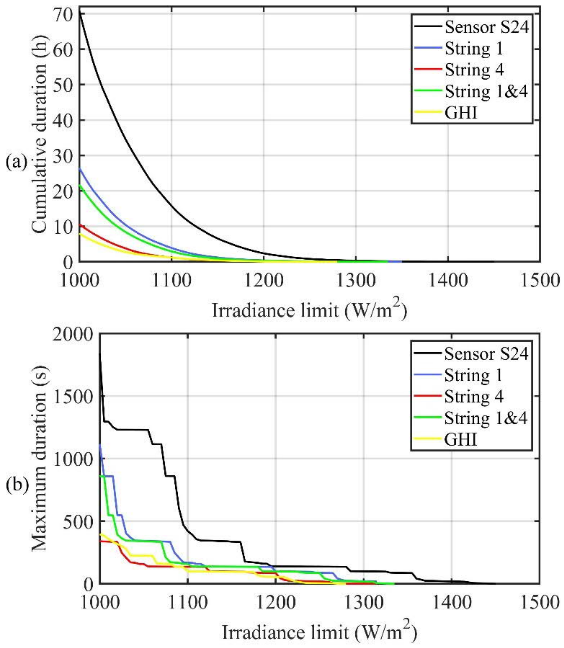

Figure 4: Cumulative (a) and maximum (b) durations of the identified CE events exceeding the irradiance limit.

for sensor S24. For the strings, the total time when the irradiance was over 1000 W/m^2 was from 11 (String 4) to 26 (String 1) hours. The maximum durations of the CE events exceeding 1000 W/m^2 for sensor S24 and String 1&4 were around 31 and 14 minutes, respectively. The average durations of these CE events were 12.8 s for sensor S24 and 17.8 s for String 1&4.

Fig. 5 presents two examples of measured CE events. In both cases, the peak irradiances of sensor S24 and String 1&4 were almost 1450 W/m^2 and 1350 W/m^2, respectively. During the shading period around 11:33 in Fig. 5 (a) the area of the PV string was shaded and the measured GHI was higher than the measured irradiances on PV modules, since the GHI sensor was exposed to a larger share of diffuse radiation. When the shading moved away, the measured on-plane irradiances exceeded the measured GHI.

3.2 CE events identified in *I–U* curve measurements

Fig. 6 presents a scatter plot between the daily highest measured power and average irradiance for the studied PV strings. The highest measured powers were 129%, 123% and 121%, with respect to the nominal STC power, for Strings 1, 4 and 1&4, respectively. The highest measured power and irradiance values are well in accord with each other. The main reason for the differences is that the operating temperature of the PV modules varies daily and is typically higher than the STC temperature of 25 °C.

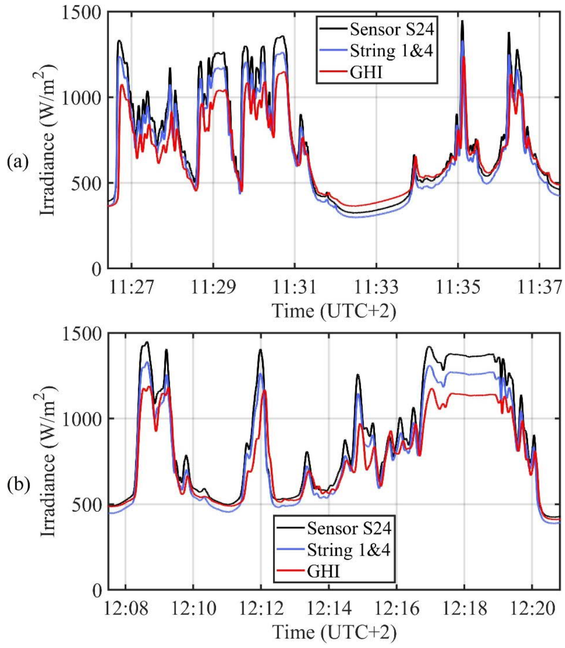

Figure 5: Measured irradiances on June 4 (a) and July 29 (b), 2022.

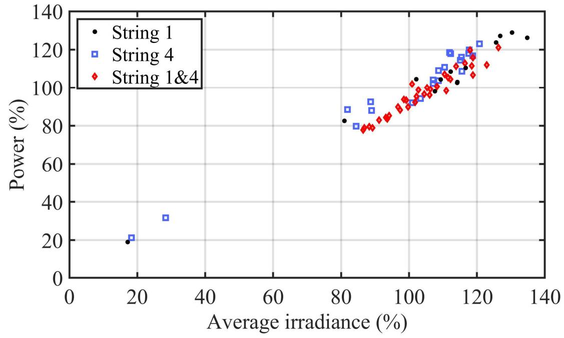

Figure 6: Scatter plot between the daily highest measured power and average irradiance for the studied PV strings.

Increase of temperature decreases the maximum power of PV modules explaining why on most days the maximum measured irradiance was slightly higher than the maximum measured PV power.

The maximum durations of the overpower events are presented in Fig. 7 as a function of the power limit. The longest durations of the events exceeding the nominal STC power are 161, 145 and 234 seconds for Strings 1, 4 and 1&4, respectively. For String 1, overpower events exceeding 1.1 times the nominal STC power and lasting over two minutes were measured. The maximum durations in Fig. 7 are a bit shorter than was reported for a 32 kW PV array based on simulations in [9] being consistent with each other.

Fig. 8 presents the relative cumulative frequencies of the measured GMPP powers and voltages for the studied PV strings during the identified overpower events, i.e., when the GMPP power exceeded the nominal MPP power. The shapes of the distributions are roughly similar for Strings 4 and 1&4 while somewhat higher powers and voltages exist for String 1. The GMPP voltages of the strings were most of the time from 80% to 100% of the nominal STC value. The GMPP voltages of the same strings were studied in [11] during whole days (from 8:00 to 18:00) and over 100% GMPP voltages were found to be much more common than in this study. The rarity of higher

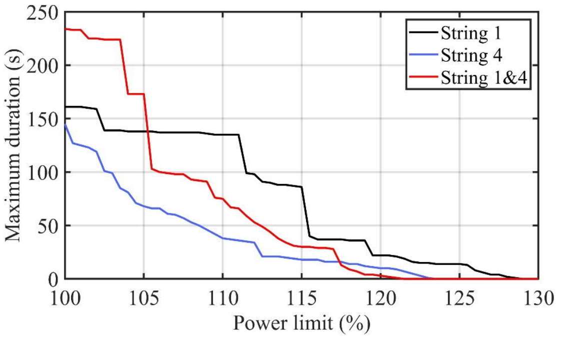

Figure 7: Maximum durations of the identified overpower events exceeding the power limit.

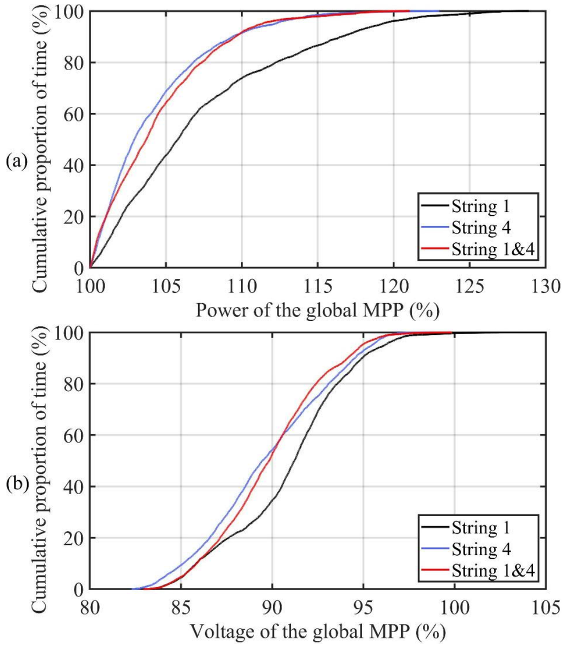

Figure 8: Relative cumulative frequencies of the GMPP power (a) and voltage (b) for the studied PV strings during the identified overpower events. The powers and voltages are with respect to the nominal MPP values.

voltage values results from the typical operating conditions of the studied PV strings under CE events: temperature was typically higher than in STC, and thus the GMPP voltages were lower than the nominal MPP voltage. The average back-sheet temperatures of the strings during the overpower events were around 30 °C. In warmer locations, even higher operating temperatures are expected. Thus, the results show that increase of PV generator operating voltages due to CE is not a problem.

Figs. 9 and 10 illustrate the behaviour of the GMPP power and voltage during CE events. The measured GMPP powers follow quite accurately the measured average irradiances of the PV strings even for the highest measured values. The measured GMPP voltage is quite steady during the CE events. Variations in the voltage exist mainly during sharp changes in the average irradiances. In these situations, the strings are partially shaded, which might lead to existence of multiple MPPs and changes in the GMPP voltage [17]. The power-voltage curves in Fig. 9 (b) measured during the CE event show that the PV string operates under nearly homogeneous irradiance conditions. The bottom curve in Fig. 9 (b) is measured during a sharp change in the average irradiance of String 1 and several local MPPs (LMPP) exist in the power–voltage curve.

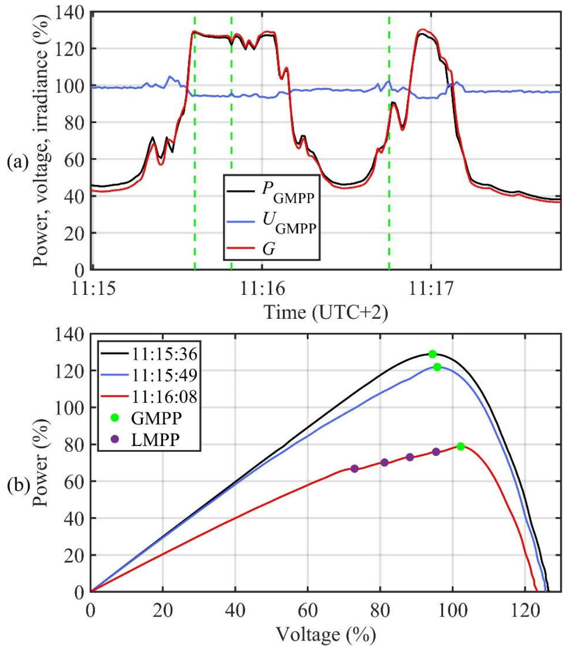

Figure 9: (a) Measured GMPP power, GMPP voltage and average irradiance of String 1 on June 16, 2022. (b) Three power–voltage curves of String 1 measured during the period presented in (a). Vertical dashed lines in (a) indicate the moments when the curves in (b) were measured.

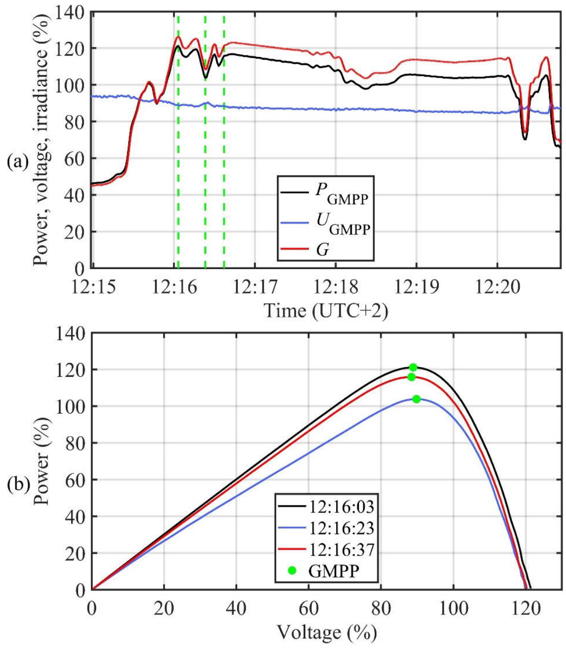

Figure 10: (a) Measured GMPP power, GMPP voltage and average irradiance of String 1&4 on July 7, 2022. (b) Three power–voltage curves of String 1&4 measured during the period presented in (a). Vertical dashed lines in (a) indicate the moments when the curves in (b) were measured.

Fig. 10 shows an example of a strong and long overpower event for String 1&4. The measured power stays one and a half minutes above 110%, with respect to the nominal power, and mainly above 100% for over four minutes. The measured power-voltage curves demonstrate that the PV strings operate under nearly homogeneous irradiance conditions during the CE event.

4 CONCLUSIONS

This paper presented an experimental study of the cloud enhancement phenomenon on PV strings. The characteristics of CE events were analysed based on irradiance measurements and the operation of three PV strings was studied under CE conditions based on measured *I–U* curves of the strings. In addition to the characteristics of overpower events, the GMPP characteristics of the strings were studied.

The highest measured irradiance was about 1.7 times the expected clear sky irradiance. Correspondingly, it was shown that PV string power can considerably exceed the highest theoretical clear sky power. Although the measured GMPP powers exceeded the nominal MPP power in STC, the GMPP voltages were typically lower than the nominal MPP voltage due to high operating temperatures. Thus, increase of PV generator operating voltages due to CE events is not a problem. In warmer locations, operating temperatures are expected to be even higher. The experimental results presented in this paper confirmed the findings of earlier simulation studies.

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REFERENCES

[1] K. Lappalainen, S. Valkealahti, Solar Energy 138 (2016) 47. http://dx.doi.org/10.1016/j.solener.2016.09.008.
[2] V. Badescu, Solar Energy 61 (1997) 251. https://doi.org/10.1016/S0038-092X(97)00057-1.
[3] K. Lappalainen, J. Kleissl, Journal of Renewable and Sustainable Energy 12 (2020) 043502. https://doi.org/10.1063/5.0007550.
[4] G.H. Yordanov, O.-M. Midtgård, T.O. Saetre, H.K. Nielsen, L.E. Norum, IEEE Journal of Photovoltaics 3 (2013) 271. https://doi.org/10.1109/JPHOTOV.2012.2213581.
[5] M. Zehner, T. Weigl, M. Hartmann, S. Thaler, O. Schrank, M. Czakalla, B. Mayer, T.R. Betts, R. Gottschalg, K. Behrens, G. König-Langlo, B. Giesler, G. Becker, O. Mayer, Proceedings 26th European Photovoltaic Solar Energy Conference, Vol. I (2011) 3935. https://doi.org/10.4229/26thEUPVSEC2011-5AO.6.3.
[6] C.A. Gueymard, Solar Energy 153 (2017) 755. http://dx.doi.org/10.1016/j.solener.2017.05.004.
[7] T. Weigl, L. Nagl, J. Weizenbeck, M. Zehner, M. Augel, P. Öchsner, B. Giesler, G. Becker, O. Mayer, T.R. Betts, R. Gottschalg, Proceedings 27th European Photovoltaic Solar Energy Conference, Vol. I (2012), 3801. https://doi.org/10.4229/27thEUPVSEC2012-5CO.7.6.
[8] J. Luoma, J. Kleissl, K. Murray, Solar Energy 86 (2012) 421. https://doi.org/10.1016/j.solener.2011.10.012.
[9] M. Järvelä, S. Valkealahti, Energies 13 (2020) 2185. https://doi.org/10.3390/en13092185.
[10] K. Lappalainen, S. Valkealahti, Proceedings 38th European Photovoltaic Solar Energy Conference, Vol. I (2021), 1264. https://doi.org/10.4229/EUPVSEC20212021-5CV.2.39.
[11] K. Lappalainen, S. Valkealahti, EPJ Photovoltaics 13 (2022) 4. https://doi.org/10.1051/epjpv/2022001.
[12] D. Torres Lobera, A. Mäki, J. Huusari, K. Lappalainen, T. Suntio, S. Valkealahti, International Journal of Photoenergy 2013 (2013) 837310. https://doi.org/10.1155/2013/837310.
[13] J. Zhang, K. Watanabe, J. Yoshino, T. Kobayashi, Y. Hishikawa, T. Doi, Japanese Journal of Applied Physics 57 (2018) 08RG11. https://doi.org/10.7567/JJAP.57.08RG11.
[14] G.H. Yordanov, T.O. Saetre, O.-M. Midtgård, Solar Energy 115 (2015) 68. https://doi.org/10.1016/j.solener.2015.02.020.
[15] G.L. Martins, S.L. Mantelli, R. Rüther, Solar Energy 231 (2022) 47. https://doi.org/10.1016/j.solener.2021.11.050.
[16] M. Järvelä, K. Lappalainen, S. Valkealahti, Solar Energy 196 (2020) 137. https://doi.org/10.1016/j.solener.2019.11.090.
[17] K. Lappalainen, S. Valkealahti, Applied Energy 301 (2021) 117436. https://doi.org/10.1016/j.apenergy.2021.117436.