



Article Performance of Monofacial and Bifacial Silicon Heterojunction Modules under Desert Conditions and the Impact of PV Soiling

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Abstract: The performance and reliability of photovoltaic (PV) modules in a desert climate depends, among other factors, on the solar irradiance, operating temperature, and soiling rate. Since the impacts of these environmental factors depend on the type of PV module technology, an assessment of the PV technology to be deployed in the desert climate is crucial for the bankability of PV projects. In this work, the indoor and outdoor performance of monofacial and bifacial silicon heterojunction PV module technologies were assessed. For the indoor measurements, a comparison of the currentvoltage (IV) characteristics was performed at standard testing condition and at different temperatures. The two module technologies showed similar temperature coefficients and expected performance within the measurement uncertainty. Comparing the specific energy yield of the modules installed in the Outdoor Test Facility (OTF), the bifacial module showed a 15% higher energy yield than the monofacial module and is attributed to the contribution of the bifacial rear side, thanks to the reflected irradiance received by the bifacial module and the high albedo of 0.43 measured at the OTF. Moreover, the bifacial module was found to be less sensitive to the PV soiling than the monofacial module. The results showed that the frequency of module cleaning could be reduced for the bifacial module compared with the monofacial module, resulting in a remarkable decrease in the module cleaning cost and PV site Operation and Maintenance cost.

Keywords: bifacial module; silicon heterojunction; albedo; soiling

1. Introduction

The recent 2022 International Technology Roadmap for Photovoltaic (ITRPV) [1] suggested that the deployment of bifacial technology would continue to increase during the coming decade, reaching 85% by 2023. Bifacial technology has the advantage of generating energy from both the front and rear side of the module; therefore, it utilizes the direct, reflected, and diffused solar irradiance. Consequently, bifacial technology shows, depending on the climate zone, a higher energy yield and a lower Levelized Cost of Electricity (LCOE) when compared with monofacial technology [2,3]. Several studies have reported a bifacial gain of up to 30% when compared to monofacial technology [4–7], and it has been correlated directly with a number of factors, including the type of installation [8], the measured ground reflectivity (albedo) [9,10], and the installation height [11].

However, only a few of these studies have addressed the impact of desert climates, where the high operating temperature and soiling are the main causes of energy yield degradation. By increasing the module temperature, the open-circuit voltage V_{oc} drops, and as a result, the PV power output decreases [12]. Silicon heterojunction (SHJ) solar cell technology demonstrated a higher open circuit voltage (V_{oc}) and a lower power temperature coefficient (TC) when compared with conventional Back Surface Field (BSF) and Passivated Emitter Rear Contact (PERC) silicon technologies. The lower voltage and power temperature coefficients of the SHJ cell reduce the impact of the operating temperature on the generated power and highlights SHJ technology as one of the best candidates for operability in high temperature climates [13–17].



Citation: Abdallah, A.A.; Kivambe, M.; Aïssa, B.; Figgis, B.W. Performance of Monofacial and Bifacial Silicon Heterojunction Modules under Desert Conditions and the Impact of PV Soiling. *Sustainability* **2023**, *15*, 8436. https://doi.org/10.3390/ su15108436

Academic Editors: Jingwei Zhang, Frank U. Hamelmann and Md. Rokonuzzaman

Received: 30 March 2023 Revised: 5 May 2023 Accepted: 11 May 2023 Published: 22 May 2023



Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). On the other hand, several studies demonstrated that the soiling of PV modules due to dust accumulation could result in a drop rate of up to 1%/day in the power output if the module is not cleaned [18,19]. The vertical mounting of the bifacial module offers the possibility of reducing the dust accumulation considerably and, therefore, reducing power losses due to soiling [20,21].

In this paper, we report on the indoor and outdoor testing of monofacial and bifacial SHJ PV modules where a comparison of the current-voltage characteristics was performed at different temperatures. Our main findings showed that the bifacial module demonstrated 15% higher energy yield than the monofacial module after a 32-month outdoor assessment, in addition to being much less sensitive to dust accumulation. Therefore, the bifacial module can potentially reduce the cleaning frequency and associated Operation and Maintenance (O&M) cost. As mentioned earlier, the bifacial gain reported here is specific for the test bench installation height and measured albedo. However, in this study, we identify PV soiling as an additional important factor that determines the bifacial gain.

2. Materials and Methods

In this section, the indoor and outdoor performance of the monofacial and bifacial SHJ PV modules are assessed. Firstly, the indoor Current-Voltage (IV) characterization at Standard Testing Conditions (STC) and at different temperature conditions is presented. Secondly, the performance of the PV modules at real outdoor operating conditions is compared for three years from 2017 to 2019. The solar irradiance data measured during the testing period and their relevance to the results is discussed.

2.1. Indoor Testing

The *I-V* curves for the monofacial and bifacial SHJ PV modules are measured in a controlled indoor testing condition using the Class A+A+A+ sun simulator (Eternal sun Spire, Hague, The Netherlands, Spi-Sun-Simulator-5100SLP). The module's electrical parameters P_{max} , V_{oc} , I_{sc} , and *FF* were extracted from the *I-V* curves at STC. The temperature performance for the SHJ PV modules was measured at different module temperatures ranging from 15 to 75 °C and a constant irradiance corrected to 1000 W/m². The temperature coefficients (*TC*) for P_{max} (TC $P_{max} \gamma$) and V_{oc} (TC $V_{oc} \beta$) were hence obtained.

2.2. Outdoor Testing

At the Outdoor Test Facility (OTF) in Doha, state of Qatar (latitude 25.33° N and longitude 51.43° E), the solar irradiance on the Plane of Array Irradiance (POA) at a tilt angle of 22° was measured. Further, the Global Horizontal Irradiance (GHI) and the Diffuse Horizontal Irradiance (DHI) were also measured. Albedo, as a key performance parameter for bifacial technology, is defined as the ratio of the reflected solar irradiance to the incident solar irradiance. At an installation height of 2 m, a pyranometer facing the ground was used to measure the reflected solar irradiance (GHI).

The data acquisition system measures the *I*-*V* characteristics of the PV modules at five-minute time intervals from the modules' electrical parameters (open-circuit voltage V_{oc} , short-circuit current I_{sc}), and at other times measures the modules at maximum power point (MPP), giving V_{mpp} , I_{mpp} , and P_{mpp} data. The modules' temperatures (T_{mod}) were measured using one thermocouple (SOL. Connect Sensor *T*, Platinum resistance temperature sensor *PT* 1000), with an accuracy of ± 1 °C. Alongside other environmental variables, the meteorological station was used to measure the ambient air temperature. Both PV modules' technologies were tested under exactly similar outdoor testing conditions with the same defined cleaning schedule to observe the impact of soiling on PV module performance.

The daily energy yield expressed in [Wh/day/Wp] was calculated from the DC energy generated from the PV module during each day of the measurement period, and normalized by its nominal Wp.

2.3. Module Characteristics

Figure 1 shows the single silicon heterojunction monofacial and bifacial PV modules under study, at the OTF and mounted at a standard tilt-angle of 22° facing south. The monofacial module uses glass in the front and white back sheet in the rear side, while the bifacial technology requires the rear side to allow light transmission, and in this case, uses glass/glass.



Figure 1. Studied PV modules as installed at the Outdoor Test Facility (OTF): (**a**) single monofacial with glass/back sheet, (**b**) single bifacial PV module with glass/glass configuration, (**c**) schematic of the solar irradiance received by the monofacial module and (**d**) that received on the rear side of the bifacial module. PT1000 thermocouple attached to the rear side of the PV module was used to measure the module temperature. Note the shading on the rear side of the bifacial module caused by the module frame.

Table 1 shows the STC module electrical parameters, as provided by the manufacturer.

PV Module	Monofacial SHJ	Bifacial SHJ
Power output, <i>P_{max}</i> [W]	235	225
Module efficiency, η [%]	18.6	16.0
Voltage at P_{max} , V_{mpp} [V]	43.0	43.2
Current at P_{max} , I_{mpp} [A]	5.48	5.21
Open-circuit voltage, Voc [V]	51.8	52.4
Short-circuit current, Isc [A]	5.84	5.54
Module dimensions [mm]	$1580\times798\times35$	$1630 \times 862 \times 35$
Temperature Coefficient (<i>TC</i>), <i>P_{max}</i> [%/°C]	-0.30	-0.29
Temperature Coefficient (<i>TC</i>), <i>V</i> _{oc} [%/°C]	-0.24	-0.24
Temperature Coefficient (TC), I_{sc} [%/°C]	0.029	0.031

Table 1. Standard Testing Conditions (STC). Module characteristics obtained from the PV module data sheet.

3. Results

In this section, firstly, the indoor *I-V* measurements at STC and at different temperatures are compared for the two SHJ modules. Secondly, the outdoor solar irradiance components and ambient temperatures measured during the testing period followed by a comparison of the energy yield for both the monofacial and bifacial SHJ modules are summarized. Finally, the performance of the two modules and the impact of the soiling on the generated PV power will be presented.

3.1. Indoor IV Measurements

The *I-V* curves of the monofacial module measured on the front side at STC is shown in Figure 2a, and the *I-V* curves of the bifacial module measured on the front and rear side at STC is shown in Figure 2b. From these *I-V* curves, the P_{max} , I_{sc} , and V_{oc} of the monofacial module are 227 W, 5.7 A, and 50.8 V, respectively, while the front P_{max} , I_{sc} , and V_{oc} of the bifacial module are 231 W, 5.6 A, and 52.4 V, respectively. For the latter, the bifaciality was calculated. The rear side STC measured parameters P_{max} , I_{sc} , and V_{oc} are 215 W, 5.2 A, and 52.3 V, respectively. The calibrated reference PV module uncertainty was \pm 7.31 [W], \pm 0.35 [V], and \pm 0.15 [A] for P_{max} , V_{oc} , and I_{sc} , respectively.



Figure 2. I-V curves measured at the STC for the (**a**) monofacial SHJ module and (**b**) bifacial SHJ module, where the measurement was performed on both the front side and the rear side to determine the module bifaciality.

Secondly, the PV modules were tested at 1000 W/m^2 and at various module temperatures of 15, 25, 50, and 75 °C in order to determine the temperature coefficient for each module (Figure 3a,b). As expected for both modules, increasing the module temperature resulted in a drop in the V_{oc} .



Figure 3. (a) I-V curve measured at a constant solar irradiance of 1000 W/m² and various module temperatures for (a) monofacial and (b) bifacial SHJ modules, and (c,d) the calculation of the temperature coefficient (TC) from the linear fit of the normalized P_{max} and normalized V_{oc} for $P_{max} \gamma$ and TC $V_{oc} \beta$, respectively.

The temperature coefficients TC Pmax and TC Voc were calculated from the linear fit of the normalized Pmax and normalized Voc (Figure 3c,d). The TC Pmax for the bifacial and monofacial modules are -0.306 and $-0.319\%/^{\circ}$ C, respectively, while the TC Voc for the bifacial and monofacial modules are -0.239 and $-0.256\%/^{\circ}$ C, respectively. The measured temperature coefficients for both Pmax and Voc are in good agreement with the values provided by the manufacturer (i.e., shown in Table 1). As expected, no significant difference in the TC for the monofacial and bifaical SHJ modules were observed.

3.2. Solar Irradiance and Meteorological Data

In order to better understand the PV performance data, it is essential to provide the mean and the range of variability of the solar irradiation and temperature data. Figure 4a shows the daily values of the solar components Plane of Array (POA), Global Horizontal Irradiance (GHI), and Diffused Horizontal Irradiance (DHI), and the ambient temperature measured during the testing period from 2017 to 2019. Higher solar irradiation and ambient temperatures were measured during the summer months. An average ambient air temperature of 31 °C was measured, and reached 40 °C during the summer months. The average daily value of the POA, GHI, and DHI was 6.3, 6.0, and 3.7 kWh/m²/day, respectively. The desert climate typical to Qatar is characterized by high DHI values due to the high scattered irradiance from the atmosphere and surroundings [22]. The average cumulative annual values of POA, GHI, and DHI during the measurement period were 2209, 2100, and 1345 kWh/m², respectively (Figure 4b). An increase in the DHI value was observed in 2019 and is mainly attributed to the increased number of cloudy, hazy, and dusty days.



Figure 4. (a) Daily solar irradiation POA, GHI, DHI, and ambient temperature, (b) cumulative yearly values of solar irradiation components measured at the OTF (Doha, Qatar) during the testing period from 2017–2019, (c) average module temperature during the year 2019.

Figure 4c shows a typical module temperature measured at OTF, in 2019, for bifacial and monofacial SHJ modules. Within the measurement uncertainty, no significant difference in module temperature was observed. From this measurement, we can conclude that the generated energy yield will not be affected by the module temperature. Additionally, we have shown in the previous section (Figure 3) that both modules had similar temperature coefficients. From our previous study, we found that the energy yield is not necessarily correlated with the TC, because its effect was smaller than that of the other variables that influenced the yield, such as Pmax changes. For the current study, and since both SHJ modules have a similar TC, we can conclude that the TC did not show a significant impact on the energy yield.

Figure 5a shows that a quite constant albedo is measured at the OTF on a brown gravel ground surface throughout the year of 2017, and no significant seasonal variation was observed. Figure 5b shows the irradiance profile for the GHI, the reflected irradiance from the ground, and the calculated albedo during a clear sky day. At a maximum GHI value of 1070 W/m² and a maximum reflected irradiance of 480 W/m², an albedo of 0.45 was calculated (note that albedo is the ratio between the reflected irradiance and the normal irradiance). Data filtering was performed by excluding outlier data at sunrise and sunset (high azimuth angles).



Figure 5. (a) Albedo counts during the year 2017, (b) daily profile of GHI, reflected irradiance, DHI, and albedo during a typical clear sky day during 2017.

3.3. Outdoor Performance

The normalized daily power profile for the monofacial and bifacial SHJ modules associated with the POA irradiance profile are presented in Figure 6a for a clear sky day. The normalized Pmax of the bifacial module is 15% higher than the Pmax of the monofacial module. The normalized I_{sc} received from the rear side is higher than the normalized Isc for the monofacial module by approximately 12%. (Figure 6b). No significant variation of the V_{oc} value was observed (Figure 6c). We can conclude from this that the main driver for the increase in P_{max} for the bifacial module is its higher I_{sc} . Further, the gain in the I_{sc} and Pmax are maximum at noon.



Figure 6. (a) Solar irradiance POA and power profile generated by the bifacial and monofacial SHJ modules on a clear sky day, (**b**,**c**) are the normalized I_{sc} and V_{oc} of the SHJ bifacial and monofacial modules measured at similar outdoor testing conditions during a clear sky day, respectively.

Figure 7a shows the cumulative specific energy yield in the years 2017 to 2019. The SHJ bifacial module showed a higher specific energy yield of 9%, 11%, and 21%, respectively. Note that for the year 2017, the data collection for monofacial modules started from March 2017. The average daily energy yield over the testing period was 5.2 Wh/day/Wp and 6.1 Wh/day/Wp for the monofacial module and bifacial SHJ modules, respectively, which is about 15% higher. The increase in the energy yield of the SHJ bifacial module is attributed to the irradiance received by the bifacial module on the rear side. The cumulative monthly energy yield for the SHJ monofacial and bifacial modules are reflected in Figure 7b. Generally, throughout the testing period, the bifacial module showed a higher energy yield compared with the monofacial module.



Figure 7. (a) Cumulative specific energy yield for bifacial and monofacial SHJ modules mounted at standard tilt angle of 22°, (b) monthly energy yield. Note: the monofacial data collection took place from March 2017–2019.

The bifacial gain therefore depends on the utilization of the albedo. The latter is a factor of various parameters, such as the incoming GHI, the surface reflectivity, fixed tilt angle vs. use of tracker, PV module rack height, shading the module rear side by the rack, and the Sun elevation angle. Similar studies [23] also reported that the bifacial gain can be increased by up to 20–30%, depending on the system design, improvement of the albedo, higher ground reflectivity, and optimized installation height. Apart from the albedo, the bifacial gain depends also on the soiling rate and the module cleaning frequency, either by rainfall and/or by a scheduled cleaning event as will be discussed in the next section.

3.4. Soiling Impact on the Performance of Monofacial and Bifacial Silicon Heterojunction Modules

In a desert climate, seasonal variation can be distinguished by winter raining months with a high soiling rate and several rainfall events from October to April, and a summer dry season with a high ambient temperature from May to September. Both PV soiling and a high operating temperature affect the performance of the PV system. As shown in Section 3.1, no significant difference in the temperature coefficient for monofacial and bifaical SHJ modules were observed; therefore, we can assume that the impact of temperature on PV performance is similar for both modules. In this section, we focus on the effect of the PV soiling on the daily energy yield.

The daily energy yield data are presented in Figure 8 for the years 2017 to 2019. Additionally, the daily normalized short-circuit current by the Plane of Array Irradiance (I_{sc} /POA) is used as a key indicator for the impact of the soiling on the module short-circuit current, and gives a clear presentation of the linear fitting of the data. Further, the scheduled cleaning, rain events, and dust storms were indicated by arrows and displayed also in Table 2. The vertical dashed-lines and the capital letters from *A* to *T* indicate the period with soiling. Generally, a drop in the energy yield and I_{sc} was observed for both the bifacial and monofacial modules due to the soiling effect. The energy yield and the (I_{sc} /POA)

losses were restored right after the module scheduled cleaning and/or after a rainfall event. For both modules, the soiling rate was determined for each soiling period (from A to T) and presented in Table 2.



Figure 8. Daily energy yield and daily normalized short-circuit current by the Plane of Array Irradiance (I_{sc} /POA) for bifacial and monofacial SHJ modules during the testing period from April 2017 to December 2019. (**a**,**b**) 2017, (**c**,**d**) 2018 and (**e**,**f**) 2019. The scheduled cleaning and rain events were indicated by arrows. The vertical dashed-lines and the letters *A* to *T* indicate the period with soiling.

Period of Soiling and Number of Days with no Cleaning	Soiling Rate [%/Day]	Comments	
	2017		
A, from 2 April to 3 May (32 days)	Monofacial 0.08%/day	-	
B, from 4 May to 4 July (62 days)	Monofacial 0.31%/day	Cleaning schedule 3–4 May. Dust storm 31 May to 1 June	
C, from 5 July to 15 August (42 days)	Monofacial 0.74%/day	Cleaning schedule 4 July. Rainy day 15 August	
<i>D</i> , from 16 August to 5 September (21 days)	Monofacial 0.82%/day	-	
<i>E</i> , from 6 September to 27 October (52 days)	Monofacial 0.59%/day	Cleaning schedule 5 September	
F, from 29 October to 16 December (49 days)	Monofacial 0.88%/day	Cleaning schedule 28–30 October	
G, from 2 April to 15 August (136 days)	Bifacial 0.31%/day	Cleaning schedule 15 August	
H, from 16 August to 17 December (124 days)	Bifacial 0.55%/day	Cleaning schedule 15 August. Rainy days 23 November and 17 December	
2018			
I, from 3 January to 24 February (53 days)	Monofacial 1.42%/day Bifacial 1.31%/day	Dust storm on 20 January. Rainy day 24 February	
J, from 5 March to 11 April (38 days)	Monofacial 1.54%/day Bifacial 1.48%/day	Cleaning schedule 5–6 March. Rainy days 17 March and 8–16 April. Dust storm on 31 March	
K, from 16 May to 2 July (48 days) L, from 3 July to 27 August (56 days)	Monofacial 0.34%/day Monofacial 0.58%/day	Rainy day 16 May Cleaning schedule 3 July	
<i>M</i> , from 30 August to 17 October (43 days)	Monofacial 0.90%/day	Cleaning schedule 28–30 August. Dust storm 15 October. Rainy day 17 October	
N, from 22 October to 28 December (68 days)	Monofacial 0.16%/day Bifacial 0.14%/day	Rainy days 18–28 October	
O, from 16 May to 17 October (155 days)	Bifacial 0.39 %/day	-	
2019			
P, from 1 January to 30 June (181 days)	-	-	
Q, from 3 July to 2 September (62 days)	Monofacial 0.48%/day Bifacial 0.39%/day	Cleaning schedule 2–3 July	
R, from 2 September to 17 October (45 days)	Monofacial 0.57%/day Bifacial 0.44%/day	Cleaning schedule 3–4 September	
S, from 18 October to 4 November (18 days)	Monofacial 0.50%/day Bifacial 0.43%/day	Rainy day 17 October	
T, from 7 November to 28 December (52 days)	Monofacial 0.02%/day Bifacial 0.03%/day	Cleaning schedule 5–7 November. Rainy days 10, 19, 25 November and 8–18 December	

Table 2. Period of PV module soiling, scheduled module cleaning, and/or cleaning by rainfall and estimated soiling rate for the bifacial and monofacial SHJ modules from 2017 to 2019.

From Figure 8a,b, the bifacial module was cleaned only two times during the period *G* and *H* with an average soiling rate of 0.86%/day (see Table 2). During this period, the monofacial module was cleaned five times, as indicated by the period *A* to *F* with an average soiling rate of 3.4%/day. From Figure 7a, we have seen that during the year 2019, the bifacial gain was only 9%. Similarly, Figure 8c,d showed the period *O* where the bifacial module was cleaned only once with an average soiling rate of 0.39%/day, while during the same period, the monofacial module was cleaned two times and indicated by the periods *K*, *L*, and *M*, with an average soiling rate of 1.8%/day. When the bifacial module is not cleaned, the monofacial module generated more energy than the bifacial module (periods *F* and *M*).

From Figure 8e,f, firstly, period *P* showed quite a low soiling rate due to the rainfall events during this specific period. Similarly, the period *T* showed a lower soiling rate due to the rainfalls during the months November and December that kept both modules cleaned. The calculated soiling rate for the bifacial and monofacial modules is 0.03%/day and 0.02%/day, respectively. Secondly, the bifacial module showed a slightly lower soiling rate when compared with the monofacial module, as clear when comparing the periods where both modules received similar cleaning scenarios. For example, the calculated soiling

rate for the bifacial module during the period *Q*, *R*, and *S* in 2019 is 0.39%/day, 0.44%/day, and 0.43%/day respectively, while the calculated soiling rate for the monofacial module is 0.48%/day, 0.58%/day, and 0.50%/day, respectively.

Negligeable soiling on the rear side of the bifacial module was observed and no module cleaning was performed on the bifacial rear side. The relevant literature also showed that the soiling rate on the rear side of the bifacial module is insignificant when compared with the front side soiling. For instance, a value of 0.039%/day was calculated by Luque et al. [20]. Hence, for the bifacial module, the rear side will contribute to the energy yield when the front side is not cleaned, and therefore, the bifacial module is less sensitive to the PV soiling than the monofacial module.

The different module cleaning scenarios applied during the testing period and the soiling rate are presented in Table 2. The period of soiling is defined as the period where the PV module is not cleaned. The soiling rate is estimated from the drop in the daily energy yield due to soiling. Dust storms were recorded once during 2017, three times during 2018, and there was no dust storm recorded during 2019.

In summary:

- The impact of soiling on the daily energy yield is considerable, and therefore module cleaning frequency and the impact of soiling should be taken into account when comparing the bifacial gain and annual energy yield generated. For example, Figure 7 shows a higher bifacial gain during the year 2019 due to the frequent module cleaning and rainfall events in a short period. Additionally, the reason for a slight higher energy yield for the monofacial module (Figure 7) compared with the bifacial module during Feburary 2018 is due to the soiling impact (see also Figure 8c,d).
- On average, the energy yield for the bifacial module is higher than that of the monofacial module, as indicated also in Figure 7.
- The bifacial module does not require a similar cleaning frequency as the monofacial module due to the lower decrease in module efficiency for the same front-side soiling.
- The results also emphasized the importance of an optimized module cleaning schedule considering rainfall events in order to reduce the module cleaning frequency and, therefore, the PV site Operation and Maintenance (O&M) cost.

4. Conclusions

This work summarizes the performance of monofacial and bifacial silicon heterojunction modules installed at 22° tilt in the desert climate condition of the state of Qatar. The bifacial SHJ module showed a 15% higher energy yield compared with the monofacial SHJ module. The increase in the energy yield is attributed to the contribution of the bifacial rear side, due to the reflected irradiance received by the bifacial module. During a clear sky day, the normalized maximum power generated by the bifacial module was found to be 12% higher than the normalized maximum power generated by the monofacial configuration, mainly due to the higher current of the former module.

In a desert climate characterized by a high operating temperature, using silicon heterojunction (SHJ) technology is advantageous due to its lower power temperature coefficient compared with other silicon technologies, such as Aluminum Back Surface Field (Al-BSF), Passivated Emitter Rear Contact (PERC), Tunnel Oxide Passivated Contact (TOPCon), and Interdigitated Back Contact (IBC). No significant difference was found in the measured module temperature coefficient for the two modules.

Finally, the soiling rate during the testing period indicated that the bifacial module was clearly less sensitive to soiling compared with the monofacial module, and is attributed to the rear-side power contribution for the bifacial module and the absence (or negligible) of the soiling on the rear side. These results demonstrated that the cleaning frequency during the summer months could be reduced for the bifacial module (compared with the monofacial module) in order to reduce the module cleaning cost and, therefore, the PV site O&M cost.

12 of 13

As a direction for further research, the current data will be used for a techno-economic study to further investigate the impact of PV performance in desert climates on the PV site economical parameters, particularly considering the O&M and lifetime costs.

Author Contributions: Conceptualization, A.A.A. and M.K.; Writing—original draft, A.A.A., M.K., B.A. and B.W.F. All authors have read and agreed to the published version of the manuscript.

Funding: This publication was made possible by NPRP grant # [NPRP11S-1220-170110] from the Qatar National Research Fund (a member of Qatar Foundation). The findings herein reflect the work, and are solely the responsibility of the authors.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

- International Technology Roadmap for Photovoltaic (ITRPV) 2022; Edition March. Available online: https://etip-pv.eu/ news/other-news/international-technology-roadmap-for-photovoltaic-itrpv-r-d-findings-from-the-13th-edition/ (accessed on 14 April 2022).
- Saw, M.H.; Khoo, Y.S.; Singh, J.P.; Wang, Y. Enhancing optical performance of bifacial PV modules. *Energy Proc.* 2017, 124, 484–494. [CrossRef]
- Rodríguez-Gallegos, C.D.; Liu, H.; Gandhi, O.; Singh, J.P.; Krishnamurthy, V.; Kumar, A.; Stein, J.S.; Wang, S.; Li, L.; Reindl, T.; et al. Global Techno-Economic Performance of Bifacial and Tracking Photovoltaic Systems. *Joule* 2020, *4*, 1514–1541. [CrossRef]
- Katsaounis, T.; Kotsovos, K.; Gereige, I.; Basaheeh, A.; Abdullah, M.; Khayat, A.; Al-Habshi, E.; Al-Saggaf, A.; Tzavaras, A.E. Performance assessment of bifacial c-Si PV modules through device simulations and outdoor measurements. *Renew. Energy* 2019, 143, 1285–1298. [CrossRef]
- 5. Yusufoglu, U.A.; Pletzer, T.M.; Koduvelikulathu, L.J.; Comparotto, C.; Kopecek, R.; Kurz, H. Analysis of the annual performance of bifacial modules and optimization methods. *IEEE J. Photovol.* **2015**, *5*, 320–328. [CrossRef]
- Park, H.; Chang, S.; Park, S.; Kim, W.K. Outdoor Performance Test of Bifacial n-Type Silicon Photovoltaic Modules. *Sustainability* 2019, 11, 6234. [CrossRef]
- Muehleisen, W.; Loeschnig, J.; Feichtner, M.; Burgers, A.R.; Bende, E.E.; Zamini, S.; Yerasimou, Y.; Kosel, J.; Hirschl, C.; Georghiou, G.E. Energy yield measurement of an elevated PV system on a white flat roof and a performance comparison of monofacial and bifacial modules. *Renew. Energy* 2021, 170, 613–619. [CrossRef]
- 8. Gu, W.; Li, S.; Liu, X.; Chen, Z.; Zhang, X.; Ma, T. Experimental investigation of the bifacial photovoltaic module under real conditions. *Renew. Energy* **2021**, *173*, 1111–1122. [CrossRef]
- Rhazi, O.L.; Chiodetti, M.; Dupuis, J.; Benyakhlef, S.; Radouane, K.; Dupeyrat, P. Optimizing the utilization of reflective materials for bifacial PV plants. In Proceedings of the 37th European Photovoltaic Solar Energy Conference and Exhibition, Online, 7–11 September 2020; pp. 1286–1291.
- Guari Borrull, M.; Scherl, A.; Kampschulte, T. Design optimization of bifacial module PV power plants based on simulation and measurements. In Proceedings of the 37th European Photovoltaic Solar Energy Conference and Exhibition, Online, 7–11 September 2020; pp. 1305–1310.
- 11. Ledesma, J.R.; Almeida, R.H.; Martinez-Moreno, F.; Rossa, C.; Martín-Rueda, J.; Narvarte, L.; Lorenzo, E. A simulation model of the irradiation and energy yield of large bifacial photovoltaic plants. *Sol. Energy* **2020**, *206*, 522–538. [CrossRef]
- 12. Green, M.A. General temperature dependence of solar cell performance and implications for device modelling. *Prog. Photovol. Res. Appl.* **2003**, *11*, 333–340. [CrossRef]
- Haschke, J.; Seif, J.P.; Riesen, Y.; Tomasi, A.; Cattin, J.; Tous, L.; Choulat, P.; Aleman, M.; Cornagliotti, E.; Uruena, A.; et al. The Impact of Silicon Solar Cell Architecture and Cell Interconnection on Energy Yield in Hot & Sunny Climates. *Energy Environ. Sci.* 2017, 5, 8–10.
- De Wolf, S.; Descoeudres, A.; Holman, Z.C.; Ballif, C. High-efficiency Silicon Heterojunction Solar Cells: A Review. *Green* 2012, 2, 7–24. [CrossRef]
- Abdallah, A.A.; El Daif, O.; Aïssa, B.; Kivambe, M.; Tabet, N.; Seif, J.; Haschke, J.; Cattin, J.; Boccard, M.; De Wolf, S.; et al. Towards an optimum silicon heterojunction solar cell configuration for high temperature and high light intensity environment. *Energy Proc.* 2017, 124, 331–337. [CrossRef]
- Taguchi, M.; Yano, A.; Tohoda, S.; Matsuyama, K.; Nakamura, Y.; Nishiwaki, T.; Fujita, K.; Maruyama, E. 24.7% Record Efficiency HIT Solar Cell on Thin Silicon Wafer. *IEEE J. Photovol.* 2014, *4*, 96–99. [CrossRef]
- 17. Fathi, N.Y.; Salem, A.A. The reliability of the photovoltaic utilization in southern cities of Libya. Desalination 2007, 209, 86–90.

- Costa, S.C.S.; Diniz, A.S.A.C.; Kazmerski, L.L. Solar energy dust and soiling R&D progress: Literature review update for 2016. *Renew. Sustain. Energy Rev.* 2016, 82, 2504–2536.
- Ganesan, K.; Winston, D.P.; Suguma, S.; Jegan, S. Performance analysis of n-type PERT bifacial solar PV module under diverse albedo conditions. Sol. Energy 2023, 252, 81–90. [CrossRef]
- 20. Grau Luque, E.; Antonanzas-Torres, F.; Escobar, R. Effect of soiling in bifacial PV modules and cleaning schedule optimization. *Energy Convers. Manag.* 2018, 174, 615–625. [CrossRef]
- Bhaduri, S.; Kottantharayil, A. Mitigation of Soiling by Vertical Mounting of Bifacial Modules. *IEEE J. Photovolt.* 2019, 9, 240–244. [CrossRef]
- Roshan, D.R.; Koc, M.; Abdallah, A.A.; Martin-Pomares, L.; Isaifan, R.; Fountoukis, C. UV Index Forecasting under the Influence of Desert Dust: Evaluation against Surface and Satellite-Retrieved Data. *Atmosphere* 2020, 11, 96. [CrossRef]
- Cuevas, A.; Luque, A.; Eguren, J.; Alamo, J.D. 50% more output power from an albedo-collecting flat panel using bifacial solar cells. Sol. Energy 1982, 29, 419–420. [CrossRef]

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