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Design and Analysis of 2 DOF (Degree Of Freedom) Tracker Control and Mirror Light Reflection of Photovoltaic System

***Abstract**. Solar Panel is an electrical energy source with a very clean operation, less maintenance, and without emission. Recently, many researchers have been experimenting with the solar tracker to be able to optimize solar radiation absorption. For that, a solar tracker control system device using 2 Degrees Of Freedom is developed. Using this device, the photovoltaic panel is expected to be perpendicular to the sun, so the panel will be moved each time depending on the sun's position so the result will be much more precise toward the direction of the sun. The purpose of the paper is to design a device consisting of mechanical, program, and electrical design. Based on the test results, it can be concluded that the solar tracker control system with 2 DOF works according to the design. The system using mirror reflection can produce output power from the photovoltaic panel up to 1,75% more than the result produced by static condition of the photovoltaic panel with output power up to 1,43% and also the result of solar tracker control system with 2 DOF (Degrees Of Freedom) without a mirror that produces output power up to 1,73%.*

Streszczenthe ie.** Panel słoneczny to źródło energii elektrycznej o bardzo czystym działaniu, mniejszej konserwacji i bez emisji. Ostatnio wielu badaczy eksperymentowało z trackerem słonecznym, aby móc zoptymalizować absorpcję promieniowania słonecznego. W tym celu opracowano system sterowania trackerem słonecznym wykorzystujący 2 stopnie swobody. Za pomocą tego urządzenia oczekuje się, że panel fotowoltaiczny będzie ustawiony prostopadle do słońca, więc panel będzie każdorazowo przesuwany w zależności od położenia słońca, dzięki czemu wynik będzie znacznie dokładniejszy w kierunku słońca. Celem pracy jest zaprojektowanie urządzenia składającego się z projektu mechanicznego, programowego i elektrycznego. Na podstawie wyników testów można stwierdzić, że układ sterowania trackerem słonecznym z 2 stopniami swobody działa zgodnie z projektem. System wykorzystujący odbicie lustrzane może wytworzyć moc wyjściową z panelu fotowoltaicznego do 1,75% większą niż wynik uzyskiwany przy stanie statycznym panelu fotowoltaicznego przy mocy wyjściowej do 1,43%, a także wynik układu sterowania trackerem słonecznym z 2 DOF (stopnie swobody) bez lustra, które wytwarzają moc wyjściową do 1,73%.* (Projekt i analiza 2 DOF (stopni swobody) kontroli śledzenia i lustrzanego odbicia światła systemu fotowoltaicznego***)

Keywords: Solar Tracker, Photovoltaic, Degrees Of Freedom (DOF), Mirror Light Reflection
Słowa kluczowe: śledzenie promienikowania słonecznego, fotowoltaika.

Introduction

Electricity is energy that is always used to fulfill the daily necessity of our needs since most electrical devices require electrical energy to be used. Solar energy is one of the renewable energy sources that have a clean and hygienic operation, with less maintenance and without emission. Nevertheless, the main problem of a solar panel is the output power with a variation that depends on solar radiation intensity. Most of the available panels are installed permanently with a constant elevation angle. Therefore, it requires component addition to achieve optimum power from PV, which is by mirror reflection. The back part of the PRC solar cell can be easily opened to enable photon collection, resulting in energy result improvement of 10% to 30% [1][2].

Relocating bifacial Photovoltaic (bPV) in a single axis can improve energy production and reduce the cost of energy [3][4]. bPV also enables it to operate at a higher temperature compared to the mPV mono facial Si PV which has operated daily at 20 degrees Celsius above the environment temperature [5][6]. With the addition of a back fraction that has high radiation, it can improve advanced operation temperature. The higher temperature will affect the temporary efficiency to be decreased through the coefficient of 0,3% to 0,4% Kelvin, and decreasing module operation duration [7]. Many strategies have been considered to give thermal management of mPV including water, evaporative refrigeration, phase change, dryer, radiation refrigeration, and selective reflector [8-16]. However, these strategies may not be compatible with the bPV, and studies of optic management and back fraction thermal are required for side photons.

In this research, we are investigating the spectrally selective mirror for light management in bPV with a single axis under a realistic operation. The spectral selective mirror is designed to improve the power output simultaneously improving the carrier generation through the anti-reflection above the gap ribbon (optic benefit) and reducing heat cell through the sub-bandgap reflection (thermal benefit), most of the operating temperatures that have increased on Si module have appeared from the light parasite absorption of sub-bandgap, that usually appear in back cell contact. In the mono facial module, the spectrally selective mirror prevents the sunlight sub-band gap from entering the cell and reduces operation temperature [17][18]. In the bifacial module, however, the sub-bandgap light can also be transmitted. The addition of spectral selective mirrors to the back ribbon gap can also trap harmful infrared radiation. Therefore it is not clear whether the addition of a spectral selective mirror in the back part can reduce the operating temperature [19-23]. Besides the reflection mirror utilization, it can also use the mechanical design of a 2 DOF solar tracker.

Most of the available panels are installed permanently with a constant elevation angle. Based on previous experiments, using the Hill Climbing method enables the system to achieve optimized output power [24]. Besides that, other research using the Neural Network method also enables achieving the optimum power and PV replacement [25][26].

The research is developing the design and comparison analysis of the control system power output of a 2 DOF (Degrees Of Freedom) Tracker and Mirror Light Reflection of a Photovoltaic Panel.

Materials and Methods

System Design and Structure

The system structure is displayed in the Block Diagram of Figure 1 below with the purpose to simplify the system's realization.

From Figure 1, the result of light intensity detected by the LDR sensor will become the reference to the Arduino Uno data process, followed by Arduino moving actuator matrix according to the value received by the LDR sensor and the actuator driver. The next step is the mechanical system of the solar panel will adjust the position between east, west, north, and south according to the programmed setting value, so the result of mechanic position adjustment becomes the feedback of the LDR sensor so that able to recapture the incoming light. Mechanical system movements will result in voltage and current that will become current sources to supply Arduino Uno, Driver, and Actuator. The mechanical design of the system is shown in Figure 2 below.

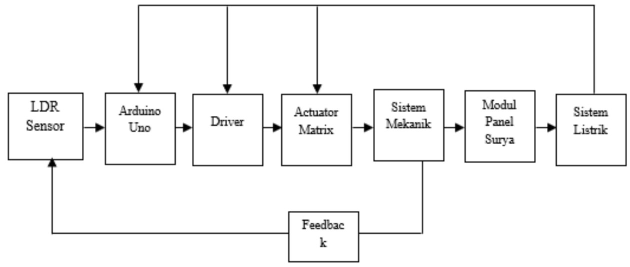

Fig. 1. Photovoltaic Panel Position Control System Design

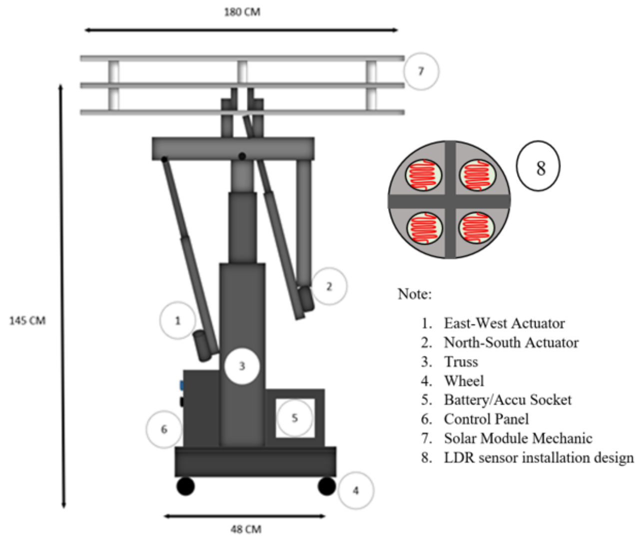

Fig. 2. Mechanical System Design

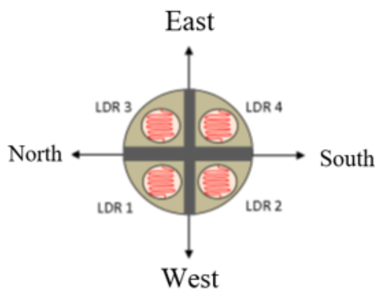

Fig. 3. LDR Sensor Position Installation

Degree Of Freedom (DOF)

The Degree Of Freedom is the impedance degree required for informing the position of a certain system at any time. In the single Degree Of Freedom system model, each mass M, damping C, and stiffness K can be focused on a single physical component with many Degrees Of Freedom [6].

Solar Power Plant

Solar Power Plant is a renewable energy resource that, at present days, is applied in rural residential. The plant achieves energy by converting the absorbed sunlight and changing it into a source of electrical energy. Sun radiation is one of the energy sources that come from nature, without being realized that it has been utilized to fulfill most human needs. This is why the solar cell is compatible to be used since it is clean, eco-friendly, and did not require fuel.

LDR Sensor Assembly

LDR that will be installed is up to four parts combined into one where each time the sensor is exposed to the brighter light then the input of the sensor will inform Arduino to move the actuator and reposition the solar panel toward the sunlight. Figure 3 describes the LDR sensor position.

The LDR position is installed according to the LDR working principle as follows:

A. Bidirectional LDR Sensor Exposed to the Sunlight

In this part, only 1 Solar Tracker movement based on the received sunlight by two sensors is illustrated in Figure 4 below.

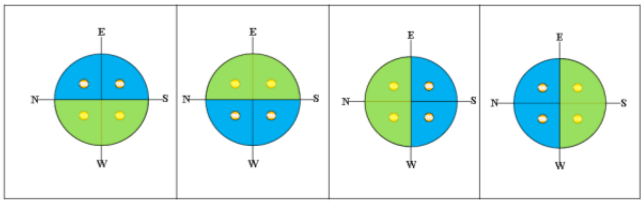

Fig. 4. Illustration of Two Sensors Exposed to the light, with Green as the exposed condition and Blue as the unexposed condition

From Figure 4, the system movements are formulated in Table 1 below.

Table 1. Table of Truth from 2 LDR Sensor exposed to the light

LDR Input				Actuator 1		Actuator 2	
LDR 1	LDR 2	LDR 3	LDR 4	E-W	E-W	N-S	N-S
1	1	0	0	1	0	0	0
1	0	1	0	0	0	0	1
0	0	1	1	0	1	0	0
0	1	0	1	0	0	1	0

B. 4 Directional LDR Sensor Exposed to the Sunlight

This section indicates that the solar panel surface is perpendicular to the sunlight where all sensors are exposed equally to the sunlight so the Arduino will not transmit orders to the two actuators to work. The system movement can be formulated in Table 2 below.

Table 2. Table of Truth from 4 LDR Sensor exposed to the light

LDR Input				Actuator 1		Actuator 2	
LDR 1	LDR 2	LDR 3	LDR 4	E-W	E-W	N-S	N-S
1	1	1	1	0	0	0	0

Results and Discussions

Voltage and Current Measurement Results

Based on the simulation result and implementation, the PV harvesting method with the Maximum Power Point Tracker (MPPT) of the Hill Climbing algorithm is the method that can be realized since the algorithm is capable to adjust to the power variation. The system consists of PV input, with Boost Converter, and is also controlled by the microcontroller. The test result can achieve 159,09 Watts of Power while the potential peak power of PV can achieve 189,79 Watts. From the implementation test result, the largest power increment is 94,9 Watts, and by experiment with the 200 WP PV characteristic, the peak power can be up to 113,68 Watts. However, this research has a weakness in that the output optimization of the PV cannot be up to optimal. It is caused by the static tracker movement of PV. It is also affected by the mirror light reflection.

This section will discuss photovoltaic efficiency analysis between static installation and dynamic installation. The analysis is done by comparison of two installation conditions, either static or dynamic. The result of measurement is in the form of voltage, current, and power calculation also regulations are shown in the following Table 3.

Table 3. Voltage and Current Measurement Result of 2 DOF in PV without a mirror and with a mirror.

Hours	Tilt Angle (PV)		2 DOF Without a Mirror			Tilt Angle (PV)		2 DOF With a Mirror			Power Regulation
	0°		Voltage	Current	Power	0°		Voltage	Current	Power	
	E-W	N-S	V	A	W	E-W	N-S	V	A	W	%
9:00	30	0	13.85	3.39	46.95	30	0	16.71	3.53	58.98	0.256
10:00	30	0	16.63	3.66	60.86	30	0	16.96	3.85	65.29	0.072
11:00	26	0	16.73	3.67	61.39	26	0	16.83	3.67	61.76	0.006
12:00	26	0	16.52	3.45	56.99	26	0	16.78	3.61	60.57	0.062
13:00	13	19	16.70	3.65	60.95	12	19	16.96	3.83	64.95	0.065
14:00	5	32	16.99	3.64	61.84	-1	32	16.75	3.73	62.47	0.010
15:00	5	32	16.70	3.34	55.77	-1	32	16.82	3.22	54.16	-0.028
16:00	5	32	14.79	2.08	30.76	-1	32	13.81	1.04	14.36	-0.053
Average			**16.11**	**3.36**	**54.44**			**16.45**	**3.31**	**55.32**	**-0.011**

Table 4. Voltage and Current Measurement Result of 2 DOF in PV by static and without a mirror (dynamic)

Hours	Tilt Angle (PV)		2 DOF Static			Tilt Angle (PV)		2 DOF Without a Mirror			Power Regulation
	0°		Voltage	Current	Power	0°		Voltage	Current	Power	
	E-W	N-S	V	A	W	E-W	N-S	V	A	W	%
9:00	0	0	16.84	2.58	43.44	30	0	13.85	3.39	46.95	0.080
10:00	0	0	17.01	3.11	52.90	30	0	16.63	3.66	60.86	0.150
11:00	0	0	16.93	3.40	57.56	26	0	16.73	3.67	61.39	0.066
12:00	0	0	17.04	3.64	62.02	26	0	16.52	3.45	56.99	-0.081
13:00	0	0	16.80	2.81	47.20	13	19	16.70	3.65	60.85	0.291
14:00	0	0	16.70	2.95	49.26	5	32	16.99	3.64	61.84	0.255
15:00	0	0	15.71	2.16	33.93	5	32	16.70	3.34	55.77	0.643
16:00	0	0	14.10	1.03	14.52	5	32	14.79	2.08	30.76	1.118
Average			**16.39**	**2.71**	**45.10**			**16.11**	**3.36**	**54.44**	**0.315**

Table 5. Voltage and Current Measurement Result of 2 DOF in PV by static and with a mirror (dynamic)

Hours	Tilt Angle (PV)		2 DOF Static			Tilt Angle (PV)		2 DOF With a Mirror			Power Regulation
	0°		Voltage	Current	Power	0°		Voltage	Current	Power	
	E-W	N-S	V	A	W	E-W	N-S	V	A	W	%
9:00	0	0	16.84	2.58	43.44	30	0	16.71	3.53	58.98	0.357
10:00	0	0	17.01	3.11	52.90	30	0	16.96	3.85	65.29	0.234
11:00	0	0	16.93	3.40	57.56	26	0	16.83	3.67	61.76	0.073
12:00	0	0	17.04	3.64	62.02	26	0	16.78	3.61	60.57	-0.023
13:00	0	0	16.80	2.81	47.20	12	19	16.96	3.83	64.95	0.376
14:00	0	0	16.70	2.95	49.26	-1	32	16.75	3.73	62.47	0.268
15:00	0	0	15.71	2.16	33.93	-1	32	16.82	3.22	54.16	0.596
16:00	0	0	14.10	1.03	14.52	-1	32	13.81	1.04	14.36	-0.011
Average			**16.39**	**2.71**	**45.10**			**16.45**	**3.31**	**55.32**	**0.234**

Table 3 above describes measurement results in two conditions of 2 DOF PV without a mirror and with a mirror. The time to gather data is set to 8 hours from 9:00 to 16:00 in West Indonesia Time, in a timestep of 1 hour. The measurement started from the tilt angle of PV measurement, then to parameter variables such as Voltage (V), Current (A), and Power (P). The experiment resulted in the average of each parameter variable.

Table 4 above describes the measurement results of 2 DOF PV by static and without a mirror (dynamic). Similar to the previous table, the time to gather data is set to 8 hours in a timestep of 1 hour. Since the 2 DOF is static, then the tilt angle (PV) of each data gathering set is constant at zero degrees Celsius.

Table 5 below describes the measurement results of 2 DOF PV by static and with a mirror (dynamic). Similar to the previous table, the time to gather data is set to zero degrees in 2 DOF static conditions.

Photovoltaic Output Graph

The graph included Voltage, Current, and Power resulting from PV in either static condition or 2 DOF without a mirror and 2 DOF with a mirror.

A. PV Voltage Graph

The graph displayed in Figure 5 above is the comparison of voltage generated by PV against time installed either by the static, 2 DOF without a mirror, or 2 DOF with a mirror. Concluding from it, the difference between the voltage resulting from 2 DOF PV using a mirror with the other condition is that the scheme produces more efficiency than the static condition and 2 DOF without a mirror.

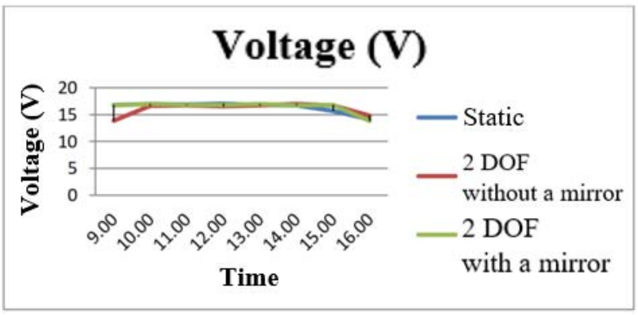

Fig. 5. Graph of PV Voltage against time in either static condition, 2 DOF without a mirror, and 2 DOF with a mirror

B. PV Current Graph

The graph displayed in Figure 6 above is the comparison of current generated by PV against time installed either by static, 2 DOF without a mirror or 2 DOF with a mirror. Concluding from it, the difference between the current resulting from 2 DOF PV using a mirror with the other condition is that the scheme produces more efficiency than the static condition and 2 DOF without a mirror.

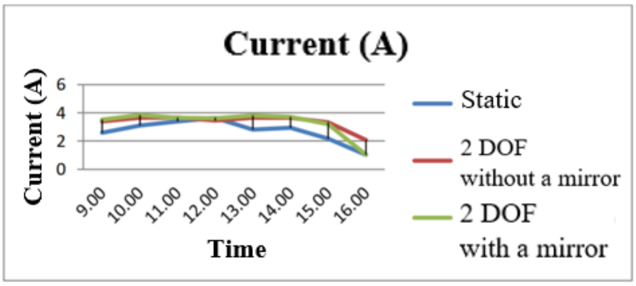

Fig. 6. Graph of PV Current against time in either static condition, 2 DOF without a mirror, and 2 DOF with a mirror

C. PV Power Graph

The graph displayed in Figure 7 is the comparison of power generated by PV against time installed either by static, w DOF without a mirror, or 2 DOF with a mirror. Concluding from it, the difference in the power resulting from 2 DOF PV using a mirror with the other condition is that the scheme produces more efficiency than the static condition and 2 DOF without a mirror.

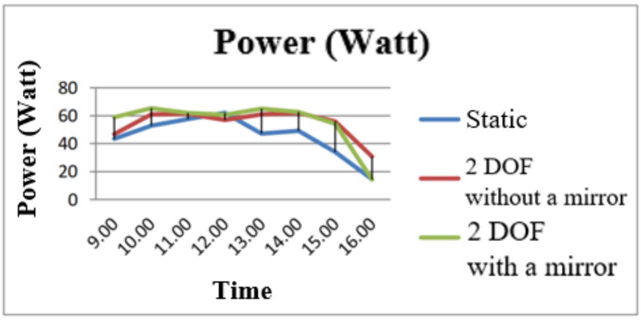

Fig. 7. Graph of PV Power against time in either static condition, 2 DOF without a mirror, and 2 DOF with a mirror

Output Efficiency Calculation

Output Efficiency Calculation is the difference between absorbed power and produced power from PV at static conditions, 2 DOF without a mirror, and 2 DOF with a mirror. The efficiency value can be calculated with the following equation.

(1) $$\boldsymbol{\eta_{PV}} = \frac{\boldsymbol{P_{maks}}}{\boldsymbol{P_{in}}} \times \mathbf{100\%}$$

With:

(2) $$\boldsymbol{P_{in}} = \boldsymbol{I_r} \times \boldsymbol{A}$$

Note: $\boldsymbol{\eta_{PV}}$ = Photovoltaic Efficiency (%); $\boldsymbol{P_{maks}}$ = Maximum Power (Watt); $\boldsymbol{P_{in}}$ = Input Power (Watt); $\boldsymbol{I_r}$ = Regulation Current (Standard = 1000 W/m); $\boldsymbol{A}$ = Photovoltaic Wide Area (m^2)

The equations are applied to the following Power Value Calculations:

$$\boldsymbol{Input\ Power\ (P_{in}) = I_r \times A}$$

With,

$$\boldsymbol{I_r = 1000\ W/m^2\ (Standard)}$$

Then,

$$\boldsymbol{Input\ Power(P_{in}) = 1000\ W/m^2 \times (P_{PV} \times I_{PV})}$$

$$\boldsymbol{Input\ Power(P_{in}) = 1000 \times (0,121 \times 0,26)}$$

PV static condition efficiency is taken from the average power output, so the calculation can be as the following:

$$\boldsymbol{\eta_{PV}} = \frac{\mathbf{45,10}}{\mathbf{31,46}} \times \mathbf{100\% = 1,43\%}$$

PV with 2 DOF without a mirror condition is taken from the average power output, so the calculation can be as the following:

$$\boldsymbol{\eta_{PV}} = \frac{\mathbf{54,44}}{\mathbf{31,46}} \times \mathbf{100\% = 1,73\%}$$

PV with 2 DOF with a mirror condition is taken from the average power output, so the calculation can be as the following:

$$\boldsymbol{\eta_{PV}} = \frac{\mathbf{55,32}}{\mathbf{31,46}} \times \mathbf{100\% = 1,75\%}$$

From the calculations above, appeared that the power efficiency of PV at 2 DOF without a mirror condition is better than static condition and 2 DOF without a mirror condition, which is 1,75% compared to 1,43% and 1,73%. There is an addition of 0,32% output efficiency of PV between static condition and 2 DOF with a mirror and an addition of 0,02% output efficiency of PV between 2 DOF without a mirror condition and 2 DOF with a mirror condition.

Output Power Comparison Result

From the comparison graph shown in Figure 8, can be known that the power efficiency of a solar panel with 2 DOF with a mirror condition are much more efficient and effective than other solar panel condition which is static, and 2 DOF without a mirror condition.

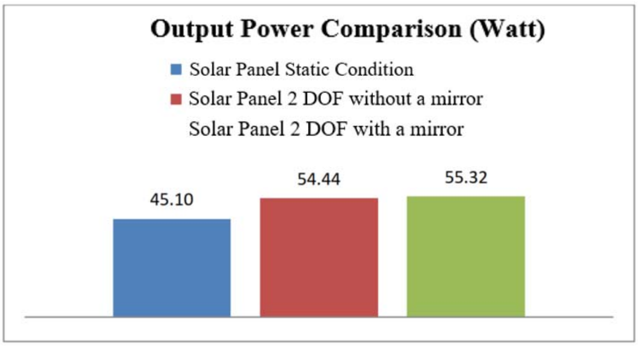

Fig. 8. Comparison Graph of Overall Output Power Average of Solar Panel

Conclusions

By the design and experiment result of a solar tracker control device with 2 DOF (Degree Of Freedom) of Solar Panel, can be concluded that the PV panel with 2 DOF with a mirror condition produces more efficiency in parameter value of voltage, current, and power compared to static condition and 2 DOF without a mirror.

In the first trial received average value of voltage and current of PV in 2 DOF without a mirror condition is 16,11 Volt and 3,36 Ampere while the average value of PV in 2 DOF with a mirror condition is 16,45 Volt and 3,31 Ampere. The comparison of efficiency between both conditions can improve the power generation efficiency to 0,02%.

In the second trial received average value of voltage and current of PV in the static condition is 16,39 Volt and 2,71 Ampere while the average value of PV in 2 DOF without a mirror condition is 16,11 Volt and 3,36 Ampere. The comparison of efficiency between both conditions can improve the power generation efficiency to 0,3%.

In the third trial received average value of voltage and current of PV in the static condition is 16,39 Volt and 2,71 Ampere while the average value of PV in 2 DOF with a mirror condition is 16,45 Volt and 3,31 Ampere. The comparison of efficiency between both conditions can improve the power generation efficiency to 0,32%.

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REFERENCES

[1] Dullweber, T., Kranz, C., Peibst, R., Baumann, U., Hannebauer, H., Fulle, A., Steckemetz, S., Weber, T., Kutzer, M., Muller, M., Fischer, G., Galinginis, P., Neuhaus, H. 2016. PERC+: Industrial PERC Solar Cells with Real Al Grid Enabling Bifaciality and Reduced Al Paste Consumption. Prog. Photovoltaics, 24 (12), 1487-1498. https://doi.org/10.1002/pip.2712
[2] Sun, X., Khan, M.R., Deline, C., Alam, M.A. 2018. Optimization and Performance of Bifacial Solar Modules: A Global Perspective. Appl. Energy, 212, 1601-1610. https://doi.org/10.1016/j.apenergy.2017.12.041.
[3] Pelaez, S.A., Deline, C., Greenberg, P., Stein, J.S., Kostuk, R.K. 2019. Model and Validation of Single Axis Tracking with Bifacial PV. IEEE J. Photovolt., 9715-721.https://doi.org/10.1109/JPHOTOV.2019.2892872
[4] Shoukry, I., Libal, J., Kopecek, R., Wefringhaus, E., Werner, J. 2016. Modeling of Bifacial Gain for Stand Alone and in-Field Installed Bifacial PV Modules. Energy Procedia, 92, 600-608. https://doi.org/10.1016/j.egypro.2016.07.025.
[5] Lamers, M.W.P.E., Ozkalay, E., Gali, R.S.R., Janssen, G.J.M., Weeber, A.W., Romijn, I.G., Van Aken, B.B. 2018. Temperature Effects of Bifacial Modules: Hotter or Cooler?. Sol. Energy Mater. Sol. Cells, 185, 192-197.https://doi.org/10.1016/j.solmat.2018.05.033
[6] Sun, X., Silverman, T.J., Zhou, Z., Khan, M.R., Bermel, P., Alam, M.A. 2017. Optics-Based Approach to Thermal Management of Photovoltaics: Selective-Spectral and Radiative Cooling. IEEE J. Photovoltaic, 7(2), 566-574.https://doi.org/10.1109/JPHOTOV.2016.2646062
[7] Dupré, O., Vaillon, R., Green, M.A. 2017. Thermal Issues in Photovoltaics and Existing Solutions. In Thermal Behavior of Photovoltaic Devices: Physics and Engineering. Springer International Publishing: Cham, pp 128.https://doi.org/10.1007/978-3-319-49457-9_1.
[8] Silverman, T.J., Deceglie, M.G., Subedi, I., Podraza, N.J., Slauch, I.M., Ferry, V.E., Repins, I. 2018. Reducing Operating Temperature in Photovoltaic Modules. IEEE Journal of Photovoltaics, 8 (2), 532–540.https://doi.org/10.1109/JPHOTOV.2017.2779842
[9] Bahaidarah, H., Subhan, A., Gandhidasan, P., Rehman, S. 2013. Performance Evaluation of a PV (Photovoltaic) Module by Back Surface Water Cooling for Hot Climatic Conditions. Energy, 59, 445–453.https://doi.org/10.1016/j.energy.2013.07.050
[10] Alami, A.H. 2014. Effects of Evaporative Cooling on Efficiency of Photovoltaic Modules. Energy Convers. Manage., 77, 668–679.
https://doi.org/10.1016/j.enconman.2013.10.019
[11] Emam, M., Ahmed, M. 2018. Cooling Concentrator Photovoltaic Systems Using Various Configurations of Phase-Change Material Heat Sinks. Energy Convers. Manage., 158, 298–314.
https://doi.org/10.1016/j.enconman.2017.12.077
[12] Simpson, L.J., Woods, J., Valderrama, N., Hill, A., Vincent, N., Silverman, T.J. 2017. Passive Cooling of Photovoltaics with Desiccants. In 2017 IEEE 44th Photovoltaic Specialist Conference (PVSC), Washington, DC, pp 1893–1897.https://doi.org/10.1109/PVSC.2017.8366065
[13] Gentle, A.R., Smith, G.B. 2016. Is Enhanced Radiative Cooling of Solar Cell Modules Worth Pursuing? Sol. Energy Mater. Sol. Cells, 150, 39–42.https://doi.org/10.1016/j.solmat.2016.01.039
[14] An, Y., Sheng, C., Li, X. 2019. Radiative Cooling of Solar Cells: Opto-Electro-Thermal Physics and Modeling. Nanoscale, 11 (36), 17073–17083.https://doi.org/10.1039/C9NR04110A
[15] Slauch, I.M., Deceglie, M.G., Silverman, T.J.; Ferry, V.E. 2018. Spectrally Selective Mirrors with Combined Optical and Thermal Benefit for Photovoltaic Module Thermal Management. ACS Photonics, 5 (4), 1528–1538.https://doi.org/10.1021/acsphotonics.7b01586
[16] Slauch, I.M., Deceglie, M.G., Silverman, T.J., Ferry, V.E. 2019. Model for Characterization and Optimization of Spectrally Selective Structures to Reduce the Operating Temperature and Improve the Energy Yield of Photovoltaic Modules. ACS Appl. Energy Mater., 2 (5), 3614–3623.https://doi.org/10.1021/acsaem.9b00347
[17] Zhou, Z., Jiang, Y., Ekins-Daukes, N., Keevers, M., Green, M. A. 2021. Optical and Thermal Emission Benefits of Differently Textured Glass for Photovoltaic Modules. IEEE J. Photovolt., 11 (1), 131–137.https://doi.org/10.1109/JPHOTOV.2020.3033390
[18] McIntosh, K.R., Abbot, M., Sudbury, B., Gueymard, C. A. 2020. Simple Model for the Atmospheric Radiative Transfer of Sunshine (SMARTS2) Algorithms and Performance Assessment
[19] Gueymard, C.A. 2001. Parameterized Transmittance Model for Direct Beam and Circumsolar Spectral Irradiance. Sol. Energy, 71 (5), 325–346.https://doi.org/10.1016/S0038-092X(01)00054-8
[20] Marion, B., MacAlpine, S., Deline, C., Asgharzadeh, A., Toor, F., Riley, D., Stein, J., Hansen, C. 2017. A Practical Irradiance Model for Bifacial PV Modules. In 2017 IEEE 44th Photovoltaic Specialist Conference (PVSC), IEEE: Washington, DC, pp 1537–1542. https://doi.org/10.1109/PVSC.2017.8366263
[21] Silverman, T. J., Deceglie, M.G. 2020. PV TOMCAT; Version 1, 2020. ASTM G173-03(2020). Standard Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37° Tilted Surface; ASTM International: West Conshohocken, PA
[22] Deline, C., MacAlpine, S., Marion, B., Toor, F., Asgharzadeh, A., Stein, J. S. 2017. Assessment of Bifacial Photovoltaic Module Power Rating Methodologies—Inside and Out. IEEE J. Photovolt., 7 (2), 575–580.https://doi.org/10.1109/JPHOTOV.2017.2650565
[23] Li, W., Shi, Y., Chen, K., Zhu, L., Fan, S. 2017. A Comprehensive Photonic Approach for Solar Cell Cooling. ACS Photonics 2017, 4 (4), 774–782.https://doi.org/10.1021/acsphotonics.7b00089
[24] Zhao, B., Hu, M., Ao, X., Xuan, Q., Pei, G. 2018. Comprehensive Photonic Approach for Djurnal Photovoltaic and Nocturnal Radiative Cooling. Sol. Energy Mater. Sol. Cells 2018, 178, 266–272.https://doi.org/10.1016/j.solmat.2018.01.023
[25] Vogt, M.R. 2015. Development of Physical Models for the Simulation of Optical Properties of Solar Cell Modules. Ph.D. Dissertation, Leibniz University, Hannover, Germany.
[26] Sujono, H.A., Sulistyowati, R., Safi'I, A., Priananda, C.W. 2018. Photovoltaic Farm with Maximum Power Point Tracker Using Hill Climbing Algorithm, ARPN Journal of Engineering and Applied Sciences, Vol. 13, 2018.
[27] Sulistyowati, R., Riawan, D.C., Ashari, M. 2017. Clustering Based Optimal Sizing and Placement of PV-DG Using Neural Network, Advanced Science Letters 23 (3), 2373-2375, 2017.