UDC 620
DOI: 10.15587/1729-4061.2021.238700

ENHANCEMENT OF ENERGY TRANSFER EFFICIENCY FOR PHOTOVOLTAIC (PV) SYSTEMS BY COOLING THE PANEL SURFACES

Hasan Shakir Majdi
Doctor of Chemical Engineering and Petroleum Industries
Department of Chemical Engineering and Petroleum Industries
Al-Mustaqbal University College
Hillah, Babil, Iraq, 51001
Mahmoud A. Mashkour
Doctor of Mechanical Engineering
Department of Mechanical Engineering*
Laith Jaafer Habeeb
Doctor of Heat Transfer and Studies
Training and Workshop Center*
Ahmad H. Sabry
Corresponding author
Doctor of Control and Automation
Institute of Sustainable Energy
Universiti Tenaga Nasional
Jalan Ikram-Uniten, Kajang, Selangor, Malaysia, 43000
E-mail: AhamadH@nuiten.edu.my
*University of Technology
Al-Sina'a str., Tel Muhammad, Baghdad, Iraq, 19006

The thermal coefficient of a solar photovoltaic (PV) panel is a value that is provided with its specification sheet and tells us precisely the drop in panel performance with rising temperature. In desert climates, the PV panel temperatures are known to reach above 70 degrees centigrade. Exploring effective methods of increasing energy transfer efficiency is the issue that attracts researchers nowadays, which also contributes to reducing the cost of using solar photovoltaic (PV) systems with storage batteries. Temperature handling of solar PV modules is one of the techniques that improve the performance of such systems by cooling the bottom surface of the PV panels. This study initially reviews the effective methods of cooling the solar modules to select a proper, cost-effective, and easy to implement one. An active fan-based cooling method is considered in this research to make ventilation underneath the solar module. A portion of the output power at a prespecified high level of battery state-of-charge (SOC) is used to feed the fans. The developed comparator circuit is used to control the power ON/OFF of the fans. A Matlab-based simulation is employed to demonstrate the power rate improvements and that consumed by the fans. The results of simulations show that the presented approach can achieve significant improvements in the efficiency of PV systems that have storage batteries. The proposed method is demonstrated and evaluated for a 1.62 kW PV system. It is found from a simultaneous practical experiment on two identical PV panels of 180 W over a full day that the energy with the cooling system was 823.4 Wh, while that without cooling was 676 Wh. The adopted approach can play a role in enhancing energy sustainability

Keywords: temperature effects on PV, cooling techniques, solar photovoltaic PV, thermal simulation, passive air cooling

Received date 08.05.2021
Accepted date 16.08.2021
Published date 31.08.2021

***How to Cite:** Majdi, H. S., Mashkour, M. A., Habeeb, L. J., Sabry, A. H. (2021). Enhancement of energy transfer efficiency for photovoltaic (PV) systems by cooling the panel surfaces. Eastern-European Journal of Enterprise Technologies, 4 (8 (112)), 83–89. doi: https://doi.org/10.15587/1729-4061.2021.238700*

1. Introduction

Solar PV is a great technology that has grown leaps and bounds particularly over the last two decades [1, 2], but its efficiency remains around 20 percent even in premium panels [3, 4]. So, only 20 percent of the energy intercepted by the solar panel is converted into electricity, the rest of the 80 percent is lost. Now, this may not be important for people who have large roof areas for installing solar panels, but for people with limited roof space like in an urban setting that 80 percent lost energy means a lot more. Even a cursory look at solar PV technology tells us that it is approaching a point of maturity [5]. Although technology development is adding extra power to the panels, these advances are only in small increments. In recent years, it is seen that there is cut cell, PRC, and bi-facial solar technologies that have improved the gain of panels, but we are now coming to a point, where to squeeze more out of the PV panels we have to look either towards the prohibitively expensive multi-junction solar cells used in satellites or bank on perovskite cells, which have the potential to go further than crystalline silicon cells [6], but at present, it remains unstable and degrades quickly. Therefore, a way to make more hay out of solar irradiance is by using a solar photovoltaic thermal (PVT) panel or what is called a photovoltaic thermal hybrid collector [7, 8]. It is a combination of solar thermal collector and photovoltaic cells, which maximize the solar gain with the simplest of methods. It provides both electricity, and heat as an output and the best thing about it is that the two technologies complement each other and work symbiotically [9, 10]. The evacuated tube collectors have been recorded with an energy efficiency of over 90 percent, which means that they can convert nearly all of the incident sunlight into heat.

Solar PV on the other hand can only work with photons in the sunlight of particular energy levels, and the rest of the photons simply pass through and get absorbed by the back layer, and end up producing heat in the cells, which is undesirable. This generated heat reduces the output of the solar cells. The thermal coefficient of the PV panel is a value that is provided with its specification sheet and tells us precisely the drop in panel performance with rising temperature. In desert climates, the PV panel temperatures are known to reach above 70 degrees centigrade, and to cool the panels down, options like cooling jackets are used [11]. In solar PVT panels, photovoltaic cells are placed on top of a solar thermal collector. The excess heat that builds up is removed by water running through the thermal collector [12, 13]. It has been claimed that hybrid panels can have efficiency as high as 85 and can generate four times the energy produced from the same surface area for only a 25 % increase in cost [14]. This cost is unaffordable with respect to some users. In Europe and many other cold climate countries, over 52 % of the total energy used goes into space and water heating. Heat remains the biggest energy and use.

Studies have shown that active heat removal systems can improve the PV panel life from 30 years to 50 years. Therefore, heat removal not only improves the instantaneous performance of the solar PV cells but also adds longevity to their life. 20 higher annual output of electricity has been reported for PV alone in a PVT system compared to a non-PVT system. Despite all these advantages, this technology is not so prevalent because PVT technology is not simply plugged and play as PV technology is. Furthermore, in summertime one can end up with large quantities of water that is 35 to 40 degrees centigrade in temperature, and has nowhere to go. For this reason, people with swimming pools are the ones that are opting to install them for now, but there is a way around it. The excess heat can be dumped by passing the hot water through outdoor convectors when it's not needed.

In many places, electricity prices are three times the price of gas [15]. This is exactly the ratio of output getting from a PVT solar panel, which are three units of heat with one unit of electricity.

A continual issue has been lowering the cost of solar photovoltaic (PV) systems. Solar PV systems are still more expensive than traditional energy sources, despite recent developments. As a result, scientific research is required to increase the performance of a PV system by lowering the surface temperature of its modules. A high output power solar system is cost-effective and adaptable as a future green energy system, especially in countries with hotter weather or lower yearly solar radiation than the STC (standard test conditions) for a solar PV system.

2. Literature review and problem statement

Several studies have shown the effect of cooling the solar panel on its performance. The authors in [16, 17] presented an estimation of photovoltaic module yearly temperature and performance based on nominal operation cell temperature calculations where a water sprinkling cooling method was used, closed cycle of water cooling [18, 19], passive heat-sink air cooling [20, 21], and active pump-based air cooling [20]. The air cooling achieves an 11.2 % increase in the output power beating upon both the water closed-cycle system (5.36 %) and the passive heat-sink air cooling system (1.41 %) [20]. This work adopts the active air cooling method by deducting a part of the delivered PV power to supply air ventilation fans to improve the system performance.

Diverse solutions have been presented to reduce the surface temperature of solar PV panels. The study computed the relationship between the temperature of PV cells and conversion efficiency [22]. Hybrid photovoltaic-thermal solar systems are reliable methods used for cooling solar PV modules [23], where PV modules are connected to a water or air cooling system for cooling solar cells. The warm water that is circulated to the solar module is used for home applications. In addition, the solar system parameters can be evaluated with the cost-effective circuitry proposed by [24]. The performance of water as a cooling agent is higher than air used as a cooling agent. The high performance of water is due to the increase in the glazing area of water. Similarly, air and passive cooling for improving the temperature of photovoltaic panels was assessed [18].

The cooling efficiency relies mainly on the design and geometry of the PV power system. The paper [17] compared one sprayed with water and the other without spray as a coolant for solar panels to improve the system efficiency, where the solar performance was higher with the sprayed water than that with direct watering but this technique consumes water. The study [25] reported the air cooling method by using ventilated channels for cooling at the bottom of each solar PV module. This technique is a passive method but requires pipes and is costly. Studies such as [26, 27] proved that using the PVT method, which also produces extra energy, is the most feasible solution to cool solar PV panels. This advantage is an important and efficient feature but it is still expensive to implement.

Nonetheless, while cooling systems that work on the glass surface are more efficient in terms of increasing system performance, they have obvious limitations and drawbacks related to the deterioration of the glass optical properties, especially if unclean cooling fluids are used, and the possibility of causing thermal shock in the glass due to extremely high temperature gradients inducing thermal shock.

Based on the above literature, more improvement is required to avoid the complexity and cost drawbacks of cooling PV top surfaces, and the costly passive or active cooling mechanisms such as spray cooling and forced convection of cooling underneath PV modules. This can be achieved by targeting simple and cost-effective methods.

3. The aim and objectives of the study

The study aims to improve the energy transfer efficiency of a solar PV system including storage batteries by cooling the bottom surface of system modules.

To achieve this aim, the following objectives are accomplished:

– to prove the effectiveness of using fan-based cooling to improve the energy transfer efficiency of a solar PV system;

– to evaluate the proposed PV modules cooling method over different values of battery SOC conditions.

4. Materials and methods

Temperature handling of solar PV modules is one of the techniques that improve the performance of such systems by cooling the bottom surface of the PV panels. An active fan-based cooling method is considered in this research as an appropriate, cost-effective, and easy to implement one to make ventilation underneath the solar module. The authors of [20] offered an experimental arrangement for a solar PV module with fans for an active air cooling system, which is considered in this study and can be shown in Fig. 1.

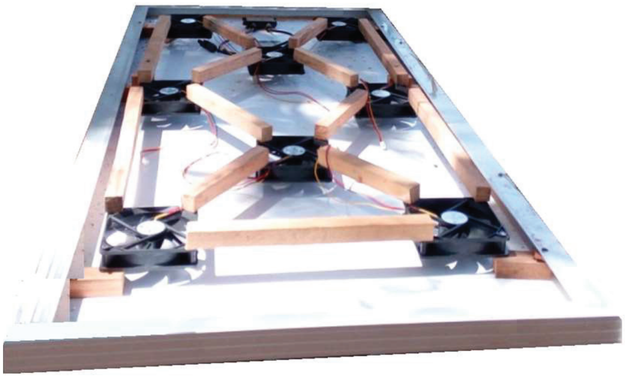

Fig. 1. The experimental arrangement for a solar PV module with fans considered in this study

A portion of the output power at a prespecified high level of battery state-of-charge (SOC) is used to feed the fans with power. The developed comparator circuit is used to control the power ON/OFF of the fans. The developed schematic diagram that is simulated by using the Matlab platform is shown in Fig. 2.

The solar cell's mathematical model is derived from its electrical representation and is mostly influenced by solar radiation and the cell's operational temperature. The relationship between the solar-induced current I_{ph} and the solar cell temperature T can be given by:

$$I_{ph}(t) = I_{ph}*\left(1 + T_{IPH}*\left(T - T_{meas}\right)\right), \tag{1}$$

T_{IPH} denotes the first-order temperature coefficient for I_{ph}, while T_{meas} is the temperature measurement parameter. The saturation current of the diode I_s and the solar cell temperature T for N number of cells are given by:

$$Is(T) = Is*\left(\frac{T}{T_{meas}}\right)^{TXIS/N} \cdot e^{\left(EG*\left(\frac{T}{T_{meas}}-1\right)/(N*V_t)\right)}, \tag{2}$$

where $TXIS$ is the temperature exponent for I_s.

The temperature T effects (in degrees C) on the open-circuit voltage V_{oc} and the short-circuit current I_{sc} [28, 29] are given by:

$$V_{ocT} = V_{oc}\left(1 + \beta_{V_{oc}}\left(T - 25\right)\right),$$
$$I_{scT} = I_{sc}\left(1 + \alpha_{I_{sc}}\left(T - 25\right)\right), \tag{3}$$

where C, β_{Voc} and α_{Isc} are the temperature coefficient in (%/deg·C), the default values are: –0.36099 %/deg·C and 0.102 %/deg·C, respectively. For the relation with the series resistance Rs and the parallel resistance Rp, the formulas are:

$$Rs(T) = Rs\left(T / T_{meas}\right)^{TRS}, \tag{4}$$

$$Rp(T) = Rp\left(T / T_{meas}\right)^{TRP}, \tag{5}$$

where TRS and TRP denote the temperature exponent for Rs and Rp, respectively.

The Matlab-based simulation setup is shown in Fig. 3.

The simulation uses the data pair of irradiance and temperature measurements as input in two identical solar array configurations but with two different controllers. The first one is traditional, whereas the second performs charge controlling via controlling cooling fans power.

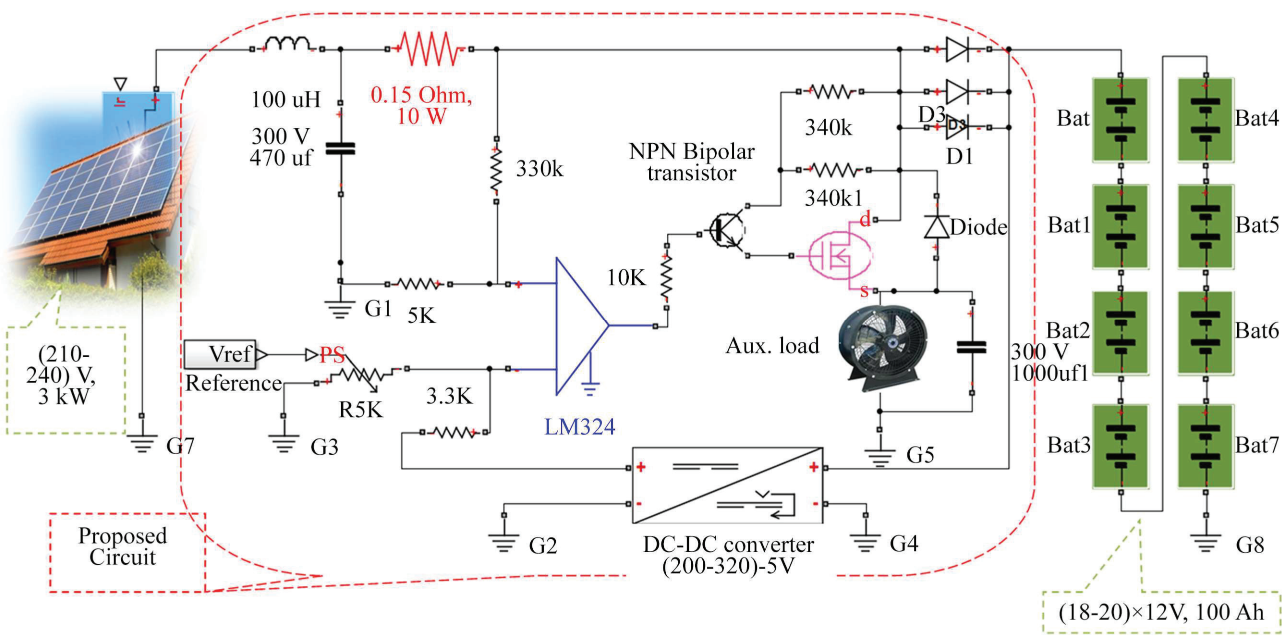

Fig. 2. The developed diagram showing the fans location in the system

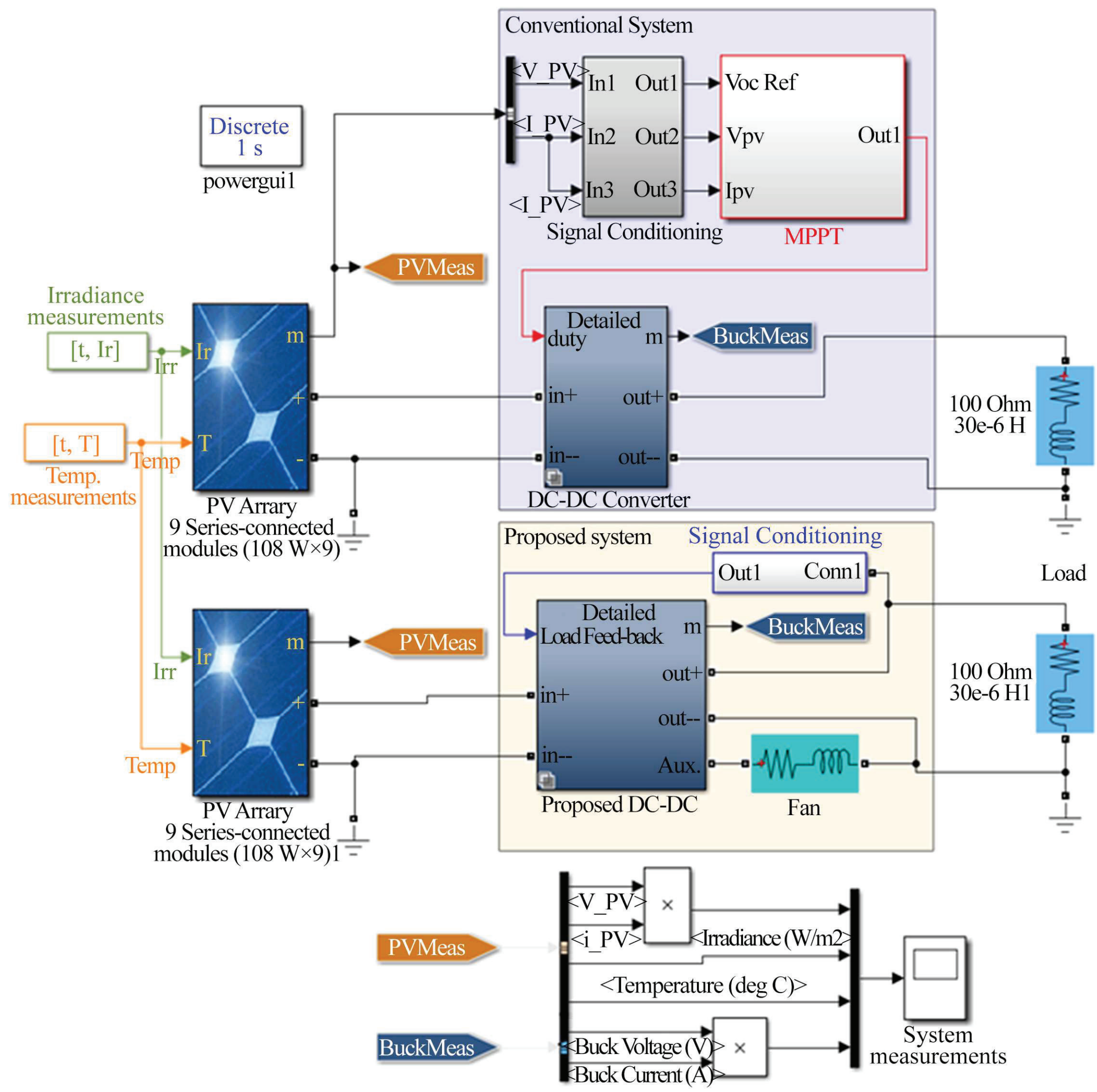

Fig. 3. Simulation setup showing the effects of cooling fans on the temperature of a PV panel

5. Results of the proposed cooling system

5. 1. Effectiveness of using fan-based cooling for energy transfer efficiency

To achieve a clear comparison and confirm the effectiveness of the air cooling for the solar PV performance, a comparison simulation setup was initially performed using two SHARP NT-185U1, 185Wp PV modules subjected to the same environmental conditions. Six PC fans, 1.92 W each, have been mounted underneath one module virtually.

Referring to Fig. 3, simulation of practical temperature and irradiance measurements was obtained from [24], these data are acquired over about 10 hours of a normal day on 31 July 2017 in University Putra Malaysia. The simulation used these practical inputs to evaluate the effectiveness of using fan-based cooling to improve the energy transfer efficiency of the solar PV system. The resulting output power over the 10 hours is shown in Fig. 4.

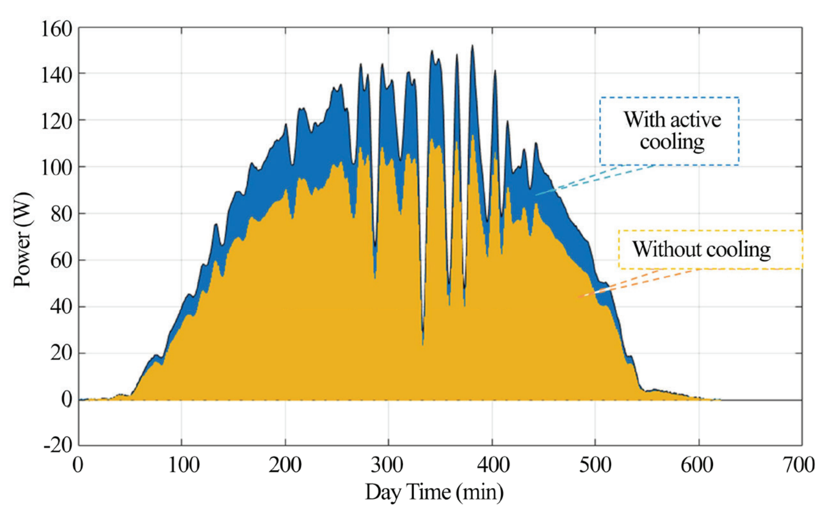

Fig. 4. The difference in the output power between the panel undercooling and that which is normal without any cooling

We can use the numerical trapezoidal method [30], or the energy is calculated by integration of the area under *Ppv* over the time T_d as follows:

$$E = \frac{1}{T_d}\int_{t_1}^{t_2} v(t) * i(t)\cdot dt = \frac{1}{T_d}\int_{t_1}^{t_2} p(t)\cdot dt, \qquad (6)$$

it is found that the energy with the cooling system was 823.4 Wh, while that without cooling was 676 Wh.

5. 2. Results of using the cooling method over different battery SOC conditions

Referring to Fig. 2, 3, the developed cooling method has been simulated using 9 serially-connected solar PV (SHARP NT-185U1, 185Wp PV modules). The parameters of the PV array and batteries can be determined for the system as listed in Tables 1, 2.

Table 1

Parameters setup for the PV array (@STC)

Solar PV module specifications	
Number of series-connected modules	9
Maximum power (W)	181.632
Voltage at max. power point, Vmp (V)	25.8
Open-circuit voltage, Voc (V)	32.4
Temperature coefficient, Voc (%/deg·C)	–0.345
Short-circuit current, Isc (A)	7.9
Current at MPP, Imp (A)	7.04
Temperature coefficient, Isc (%/deg·C)	0.063

Table 2

Parameters setup for the PV system batteries

Lead-acid battery specifications	
Nominal voltage (V)	204
Rated capacity (Ah)	60
Initial state-of-charge (%)	40, 60, 80
Fully charged voltage, V_{Fch} (V)	220
Capacity (Ah) at nominal voltage	18.6

The developed cooling method has been simulated with a solar PV system including storage batteries with a PV of 1.62 kW power and batteries of 65 Ah and (17×12 V=204 V) nominal voltage. In both results, the load was connected after 2.8 hours. The fans start running according to the algorithm demonstrated in the flowchart in Fig. 5.

In order to show the effectiveness of the proposed cooling mechanism for improving PV module generation, a MATLAB-based simulation experiment has been conducted, based on Fig. 2, to acquire measurements on two scenarios; one starting at 20 % battery SOC, without cooling fans, and the other at 60 % battery SOC with cooling fans.

For each temperature, the optimal current function has been computed. The control mechanism monitors the module's current, generated power, and temperature. The temperature has been employed as a variable that varies depending on the environment, including weather conditions and operation of the fans. Irradiance determines the highest power and best current when the temperature is known. As a result, power follows a curve that is solely dependent on irradiance. Therefore, the equations (1)–(5) are used to calculate the PV power in Fig. 6, 7.

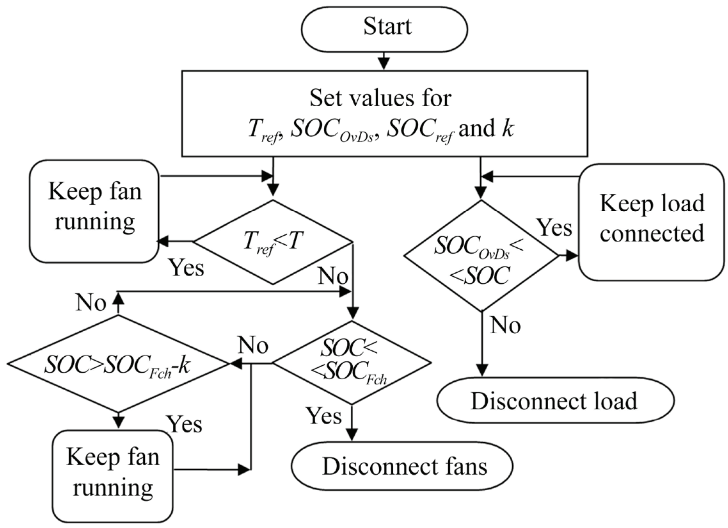

Fig. 5. The proposed algorithm of controlling fans running

Fig. 6, 7 demonstrate the variations of each of the inputs (irradiance and surface temperature), the outputs (including fan, battery, PV load) of power rates, and the battery SOC, as well as the ideal maximum power point values (MPP).

The mark (ΔP) in the last plot indicates that the proposed cooling method of PV modules shows that after MPP tracking, the produced solar PV power was shifted up to increase the PV generation. Therefore, running of fans will not only improve the power output but also shorten the time of battery SOC to being fully charged.

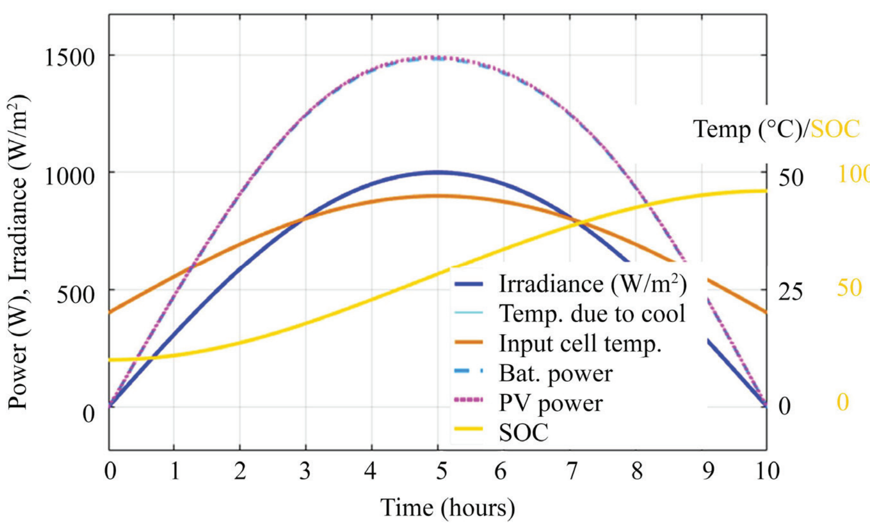

Fig. 6. Simulation measurements when starting at 20 % battery SOC, without cooling fans

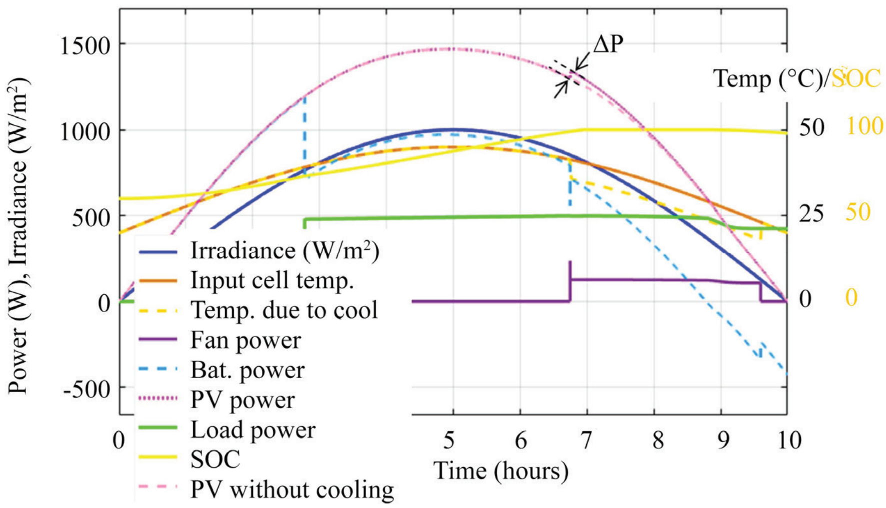

Fig. 7. Simulation measurements when starting at 60% battery SOC with cooling fans

6. Discussion of the results of the proposed cooling system

The result in Fig. 4 shows that the developed system is well performed when using two identical SHARP NT-185U1, 185Wp PV modules were subjected to the same environmental conditions. The energy harvested with active air ventilation was 823.4 Wh, which is significantly higher than that gained when no cooling method was used (676 Wh). This result has satisfied the first objective of this study by proving the effectiveness of using fan-based cooling to improve the energy transfer efficiency of storage battery-based solar PV systems. The results of Fig. 6, in which the fans were not running, show that after following the solar PV output power, the battery power was changed and went to its negative value. This negative power of the system battery indicates that it starts consuming power from its energy, while there is no change with the fan's power from zero as expected. The energy harvested (E) from this simulation is calculated using eq.(6), which is found to equal 9554.4 Wh. In contrast, the results of Fig. 7, in which the fans start running according to two reference parameters (battery SOC and the module surface temperature), show that after MPP tracking, the produced solar PV power was shifted up to increase the PV generation, as indicated with (ΔP) in the plot. The energy harvested of this simulation is found to equal 9796.2 Wh.

Therefore, the running of fans not only improves the power output but also shortens the time of battery SOC to being fully charged. The findings show that the recommended cooling method, which was based on preliminary research, performs superior energy harvesting when the fan is turned on throughout the day without the use of advanced algorithms. More energy harvesting is expected when a good control strategy is implemented, depending on the temperature reached by the module rear surface and considering the cooling operation during the day's peak hours.

The disadvantage of such technology is the power consumption from the generation, which can be considered as a self-consumption power if we integrate this type of cooling with the PV module. Passive fans or dynamic physics ventilation may be alternatives to this cooling method in future research work.

7. Conclusions

1. The effectiveness of using fan-based cooling to improve the energy transfer efficiency of the solar PV system is validated through the results, which shows that the developed system is well performed. The energy harvested with active air ventilation is significantly higher than that gained when no cooling method was used. More than 147 Wh of daily energy can be practically gained when cooling the bottom surface from each PV module of 185 W power.

2. The proposed PV modules cooling method over different values of battery SOC conditions is evaluated via the results of this study, in which the fans start running according to two reference parameters (battery SOC and the module surface temperature), showing that after MPP tracking, the produced solar PV power was shifted up to increase the PV generation, as indicated with (ΔP) in the plot. Running of fans not only improves the power output but also shortens the time of battery SOC to being fully charged. The harvested energy from these simulation results was found to equal 9,791 Wh as compared to 9554.4 Wh when no cooling was used. The proposed cooling systems can be programmed with more sophisticated and optimized control strategies to obtain further improvement in system efficiency.

References

1. Wilson, G. M., Al-Jassim, M., Metzger, W. K., Glunz, S. W., Verlinden, P., Xiong, G. et. al. (2020). The 2020 photovoltaic technologies roadmap. Journal of Physics D: Applied Physics, 53 (49), 493001. doi: https://doi.org/10.1088/1361-6463/ab9c6a
2. Sabry, A. H., Hasan, W. Z. W., Kadir, M. A., Radzi, M. A. M., Shafie, S. (2017). Photovoltaic-Powered Smart Home System with Direct Current-Environment. Journal of Computational and Theoretical Nanoscience, 14 (9), 4158–4173. doi: https://doi.org/10.1166/jctn.2017.6882
3. Hansen, C., Unruh, D., Zimanyi, G. T. (2020). TRIDENS: TRansport In DEfected Nanoparticle Solids Simulator for Nanoparticle Solar Cells. 2020 47th IEEE Photovoltaic Specialists Conference (PVSC). doi: https://doi.org/10.1109/pvsc45281.2020.9300972
4. Lan, C. W., Yang, Y. M., Yu, A., Wu, Y. C., Hsu, B., Hsu, W. C., Yang, A. (2015). Recent Progress of Crystal Growth Technology for Multi-Crystalline Silicon Solar Ingot. Solid State Phenomena, 242, 21–29. doi: https://doi.org/10.4028/www.scientific.net/ssp.242.21
5. Ju, X., Xu, C., Hu, Y., Han, X., Wei, G., Du, X. (2017). A review on the development of photovoltaic/concentrated solar power (PV-CSP) hybrid systems. Solar Energy Materials and Solar Cells, 161, 305–327. doi: https://doi.org/10.1016/j.solmat.2016.12.004

6. Bhatnagar, Y., McComb, B., Tang, J., Subramani, M., Wang, W. D., Zhang, H. et. al. (2010). Textured AZO on silicon oxy-nitride barrier films for enhanced light trapping in micromorph tandem junction solar cells. 2010 35th IEEE Photovoltaic Specialists Conference. doi: https://doi.org/10.1109/pvsc.2010.5614547
7. Pardo García, N., Zubi, G., Pasaoglu, G., Dufo-López, R. (2017). Photovoltaic thermal hybrid solar collector and district heating configurations for a Central European multi-family house. Energy Conversion and Management, 148, 915–924. doi: https://doi.org/10.1016/j.enconman.2017.05.065
8. Anand, B., Shankar, R., Murugavelh, S., Rivera, W., Midhun Prasad, K., Nagarajan, R. (2021). A review on solar photovoltaic thermal integrated desalination technologies. Renewable and Sustainable Energy Reviews, 141, 110787. doi: https://doi.org/10.1016/j.rser.2021.110787
9. Gürlich, D., Dalibard, A., Eicker, U. (2017). Photovoltaic-thermal hybrid collector performance for direct trigeneration in a European building retrofit case study. Energy and Buildings, 152, 701–717. doi: https://doi.org/10.1016/j.enbuild.2017.07.081
10. Conti, P., Schito, E., Testi, D. (2019). Cost-Benefit Analysis of Hybrid Photovoltaic/Thermal Collectors in a Nearly Zero-Energy Building. Energies, 12 (8), 1582. doi: https://doi.org/10.3390/en12081582
11. Sarafraz, M., Safaei, M., Leon, A., Tlili, I., Alkanhal, T., Tian, Z. et. al. (2019). Experimental Investigation on Thermal Performance of a PV/T-PCM (Photovoltaic/Thermal) System Cooling with a PCM and Nanofluid. Energies, 12(13), 2572. doi: https://doi.org/10.3390/en12132572
12. Wang, Y., Rao, Z., Liu, J., Liao, S. (2020). An optimized control strategy for integrated solar and air-source heat pump water heating system with cascade storage tanks. Energy and Buildings, 210, 109766. doi: https://doi.org/10.1016/j.enbuild.2020.109766
13. Delač, B., Pavković, B., Lenić, K. (2018). Design, monitoring and dynamic model development of a solar heating and cooling system. Applied Thermal Engineering, 142, 489–501. doi: https://doi.org/10.1016/j.applthermaleng.2018.07.052
14. Sun, W., Yang, Q., Fang, H., Zhang, Y., Guan, D., Lu, W. (2013). Application of heating system with active heat storage-release and heat pump in solar greenhouse. Transactions of the Chinese Society of Agricultural Engineering. doi: https://doi.org/10.3969/j.issn.1002-6819.2013.19.021
15. Lu, H., Ma, X., Ma, M., Zhu, S. (2021). Energy price prediction using data-driven models: A decade review. Computer Science Review, 39, 100356. doi: https://doi.org/10.1016/j.cosrev.2020.100356
16. Sahay, A., Sethi, V. K., Tiwari, A. C., Pandey, M. (2015). A review of solar photovoltaic panel cooling systems with special reference to Ground coupled central panel cooling system (GC-CPCS). Renewable and Sustainable Energy Reviews, 42, 306–312. doi: https://doi.org/10.1016/j.rser.2014.10.009
17. Alonso García, M. C., Balenzategui, J. L. (2004). Estimation of photovoltaic module yearly temperature and performance based on Nominal Operation Cell Temperature calculations. Renewable Energy, 29 (12), 1997–2010. doi: https://doi.org/10.1016/j.renene.2004.03.010
18. Tang, X., Quan, Z., Zhao, Y. (2010). Experimental Investigation of Solar Panel Cooling by a Novel Micro Heat Pipe Array. Energy and Power Engineering, 02 (03), 171–174. doi: https://doi.org/10.4236/epe.2010.23025
19. Valadez, T. N., Norton, J. R., Neary, M. C. (2015). Reaction of Cp*(Cl)M(Diene) (M = Ti, Hf) with Isonitriles. Journal of the American Chemical Society, 137 (32), 10152–10155. doi: https://doi.org/10.1021/jacs.5b06654
20. Khan, M., Ko, B., Alois Nyari, E., Park, S., Kim, H.-J. (2017). Performance Evaluation of Photovoltaic Solar System with Different Cooling Methods and a Bi-Reflector PV System (BRPVS): An Experimental Study and Comparative Analysis. Energies, 10 (6), 826. doi: https://doi.org/10.3390/en10060826
21. Flow Simulation Improves Photovoltaic Solar Panel Performance. Whitepaper by Schuco Using Flowmetrics (2008). Schuco.
22. Dubey, S., Tiwari, G. N. (2008). Thermal modeling of a combined system of photovoltaic thermal (PV/T) solar water heater. Solar Energy, 82 (7), 602–612. doi: https://doi.org/10.1016/j.solener.2008.02.005
23. Tonui, J. K., Tripanagnostopoulos, Y. (2007). Improved PV/T solar collectors with heat extraction by forced or natural air circulation. Renewable Energy, 32 (4), 623–637. doi: https://doi.org/10.1016/j.renene.2006.03.006
24. Sabry, A. H., Hasan, W. Z. W., Kadir, M. A., Radzi, M. A. M., Shafie, S. (2018). Wireless Monitoring Prototype for Photovoltaic Parameters. Indonesian Journal of Electrical Engineering and Computer Science, 11 (1), 9. doi: https://doi.org/10.11591/ijeecs.v11.i1.pp9-17
25. Ibrahim, M., Zinsser, B., El-Sherif, H., Hamouda, E., Georghiou, G. E., Schubert, M., Werner, J. H. (2009). Advanced Photovoltaic Test Park in Egypt for Investigating the Performance of Different Module and Cell Technologies. Conference: 24 Symposium Photovoltaische Solarenergie.
26. Rajaee, F., Rad, M. A. V., Kasaeian, A., Mahian, O., Yan, W.-M. (2020). Experimental analysis of a photovoltaic/thermoelectric generator using cobalt oxide nanofluid and phase change material heat sink. Energy Conversion and Management, 212, 112780. doi: https://doi.org/10.1016/j.enconman.2020.112780
27. Abdullah, A. L., Misha, S., Tamaldin, N., Rosli, M. A. M., Sachit, F. A. (2020). Theoretical study and indoor experimental validation of performance of the new photovoltaic thermal solar collector (PVT) based water system. Case Studies in Thermal Engineering, 18, 100595. doi: https://doi.org/10.1016/j.csite.2020.100595
28. PV Array. Implement PV array modules. MathWorks. Available at: https://www.mathworks.com/help/physmod/sps/powersys/ref/pvarray.html
29. Gow, J. A., Manning, C. D. (1999). Development of a photovoltaic array model for use in power-electronics simulation studies. IEE Proceedings - Electric Power Applications, 146 (2), 193. doi: https://doi.org/10.1049/ip-epa:19990116
30. Waluyo, Sawitri, K., Hamlar, F. (2020). Comparative computations on supplied and lost energy utilizing numerical integrations. Electrotehnica, Electronica, Automatica (EEA), 68 (2), 32–40.