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Comparative Study on the Effect of Forced Air Cooling on Electrical and Thermal Performance Efficiency of a Solar PV Module

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Abstract:

High operating temperatures limit the efficiency of solar photovoltaic (PV) modules. Forced air-cooling is a simple and cost-effective method to remove excess heat and improve PV performance. This study experimentally investigates the effect of forced air cooling on both electrical and thermal performance efficiency of a standard solar PV module under Sokoto State climatic conditions. Measurements of voltage, current, solar irradiance, module temperature, and airflow were conducted over five consecutive days. Results show that forced air-cooling enhances electrical efficiency, with peak values reaching 10.52%, and significantly reduces module temperature, increasing thermal efficiency up to 37.56%. The study highlights the dual benefit of forced air cooling and provides guidance for optimizing PV system performance in hot climates.

Keywords: *Keywords: Renewable energy, Solar PV module, Forced air cooling, Electrical efficiency, Thermal efficiency*

1. Introduction

Solar PV modules are sensitive to high temperatures, which reduce their electrical output and overall efficiency (Sengupta et al., 2018). Cooling strategies such as forced air techniques have been explored to maintain module temperature within optimal limits (Njomo et al., 2020).

Forced air-cooling is particularly attractive for small- to medium-scale PV systems due to its simplicity, availability, low cost, and ease of installation. It has widely been used to extracts excess heat from the surface of the PV module (Hamed et al., 2019). Study reported efficiency gains ranging from 5–15%, depending on environmental conditions and cooling design (Agyekum et al., 2021; Mittag & Hohm, 2019).

In other hand, thermal performance efficiency of PV modules is also affected by higher temperature. While many studies focus solely on electrical efficiency, the thermal performance of PV modules is equally critical, especially in hot climates, as it directly affects energy output and longevity (Agyekum et al., 2021; Mittag & Hohm, 2019).

Assi et al., (2012), carried out experimental investigation, forcedly using air from air-conditioning fans to flow directly to the solar PV module. The experimental result shown that the force air is capable of cooling the PV module and removing the dust accumulated over the solar PV module's front surface, leads to a great improvement in the performance efficiency of the PV module. This study is an upgrade of the Pape: "effect of forced air cooling on the electrical performance efficiency of a solar photovoltaic (PV) module", with additional focus on temperature measurements of the module and airflow. It evaluates the effect of forced air cooling on both electrical and thermal performance efficiency, providing a comprehensive understanding of its benefits under real-world conditions in Sokoto State, Nigeria.

2. Materials and Methods

2.1 Experimental Materials

Materials utilized are 2 identical PV modules (SOL-SH180, SUNSHINE SOLAR), DC fan (RM-SK-20220160, SUNKING), Solar power meter (SL102, Di-LOG), Digital multimeters (DT9205A, ANENG), Digital infrared thermometer (GM320 IR, BENETECH), Digital anemometer (TAB161, TASi), Plastic meter rule, and Digital stopwatch. All PV modules and measuring instruments were obtained at Sokoto Energy Research Center (SERC), while the auxiliary materials such as DC fan; meter rule; and stopwatch were sourced at the local Ranganda Market, village in Gwadabawa local government of Sokoto State, Nigeria.

2.2 Experimental Setup

Two PV modules were set up side by side. First module served as natural air-cooling module, and second module served as forced air-cooling module. The forced air-cooling module was equipped with a DC fan to blow air across its surface. For the natural air-cooling module, natural air was allowed to flows over its surface. All modules were tilted at 3° north to optimize solar incidence.

2.3 Data Collection and Calculations

Electrical measurements (voltages and currents) were taken with multimeters, while module temperatures were recorded with an infrared thermometer. Simultaneously, solar irradiance was measured using a solar power meter and ambient wind speed was also measured using anemometer to ensure consistency across experiments.

2.4 Input and Output Solar Electrical Power and Thermal Energy

2.4.1 Input Solar Electrical Power and Thermal Energy

Input electrical power (P_{in}) was calculated based on solar irradiance and module area. The model utilized was given by Sengupta et al., (2018) as;

$$P_{in} = I_s \, . \, A \quad \text{..... (3.1)}$$

Where: I_s = the solar irradiances, and A = the area of each module,

Input thermal energy (Q_{in}) was calculated based on solar irradiance and module area with respect to the measurement interval. The model utilized was given by Njomo, et.al (2020) as;

$$Q_{in} = I_s \, . \, A. \, T \quad \text{..... (3.2)}$$

Where: T = the time interval for taken the measurement (s)

2.4.2 Output Electrical Power and Thermal Energy

Output electrical power (P_{out}) was calculated based on electrical voltage and current. The model utilized was given by Electrical Technology (2020), as:

$$P_{out} = V_{max} \times I_{max} \quad \text{..... (3.3)}$$

Where: V_{max} = the maximum voltage, and I_{max} = the maximum current

Output thermal energy ($Q_{o.a}$) removed by forced air cooling was estimated and calculated using a model given by Frontiers in Energy Research (2022) as;

$$Q_{o.a} = H \, . \, A \, . \, \Delta\theta \quad \text{..... (3.4)}$$

Where: H = heat transfer coefficient ($Wm^{-2}K^{-1}$) and $\Delta\theta$ = module's temperature change (°C)

2.4.3 Electrical and Thermal Efficiency

The electrical efficiency (η_{el}) of the module is related to the input and output solar electric power. The model utilized was given by Agyekum et al (2021), as:

$$\eta_{el} = \frac{P_{out}}{P_{in}} \text{ x } 100\% \quad \text{..... (3.6)}$$

Where: P_{out} = outputs electric power and P_{in} = inputs electric power of the modules.

The thermal efficiency η_{th} of the module is related to the input and output solar thermal energy. The model utilized was given by Mittag and Hohm (2019), as:

$$\eta_{th} = \frac{Q_{ou}}{Q_{in}} \text{ x } 100\% \quad \text{..... (3.7)}$$

Where: Q_{ou} = quantity of outputs heat energy, and Q_{in} = quantity of inputs heat energy.

3. Results and Discussion

3.1 Experimental Setup

Figure 3.1 is the experimental research work, properly setup and conducted at Sokoto Energy Research Center (SERC). The PV modules used were of the same model, rating, and surface area, and installed in the same tilt angle, orientation, and environmental conditions. The model for the modules' effective area (A_f) was given by Energypedia (2024) as;

$$A_f = n_c \text{ X } a_c = 0.8m^2 \quad \text{..... (4.1)}$$

Where n_c = 36, number cells, and a_c = $0.022m^2$, area of each cell.



Figure 3.1Experimental setup

3.2 Data Measured and Collected

At two rheostat settings (9Ω and 18Ω), the Voltages and currents of each module were measured. The wind speeds, modules' temperatures, and solar irradiances were measured, averaged, and recorded in table A. The forced air flow rate was approximately measured as 2.5 m s^{-1}. Simultaneously, all the measurements were taken after every 30s, from 8:00 a.m. to 5:00 p.m., to capture a diurnal variation (Ji et.al., 2021).

Table A: Solar irradiance and input power and heat with wind speeds

Time	Irradiance	Input Power	Input Heat	Wind
8:30am	446.2	356.8	178.4	0.18
9:00am	480.2	384.2	192.4	0.3
9:30am	563	450.4	225.2	0.38
10:00am	558	446.2	223.4	0.56
10:30am	596.8	477.4	238.6	0.44
11:00am	567.2	453.8	226.8	0.52
11:30am	554.6	443.8	222	0.26
12:00pm	578.2	462.4	231.4	0.42
12:30pm	605.2	484.2	242.2	0.64
1:00pm	523.8	419	209.6	0.82
1:30pm	546.2	436.8	218.6	0.76
2:00pm	575.4	460.4	230.2	0.64
2:30pm	575.6	460.4	230.2	0.14
3:00pm	518	414.4	207.2	0.28
3:300pm	474.4	379.6	189.8	0.28
4:00pm	412.6	330	165	0.48
4:30pm	399	322.8	161.4	0.48
5:00pm	312.8	250.2	125	0.34

3.3 Solar Input and Output Power and Heat

Table BSolar output power and heat of natural and forced air-cooling module

Time	Natural Air-Cooling Module		Forced Air-Cooling Module	
	Output	**Output Heat**	**Output Power**	**Output Heat**
8:30am	28.26	73.42	37.56	36.9
9:00am	28.2	66.9	34.3	54.96
9:30am	27.1	65.8	35.68	52.78
10:00am	32.88	70.3	34.22	43.46
10:30am	31.44	74.86	35.42	37.1
11:00am	30.78	64.2	35.1	39.88

11:30am	31.2	56.54	37.86	39.3
12:00pm	31.24	71.76	34.72	41.86
12:30pm	30.18	72.16	33.42	53.76
1:00pm	30.64	58.06	33.92	53.4
1:30pm	30.24	53.12	33.92	53
2:00pm	27.2	61.7	28.96	37.68
2:30pm	28.02	43.94	30.84	46.82
3:00pm	24.84	56.36	29.44	36.12
3:300pm	24.52	62.2	28.16	46.24
4:00pm	23.84	59.72	29.9	59.52
4:30pm	24.3	60.78	26.54	51.78
5:00pm	21.08	42.6	21.02	36.1

Figure 3.2 presents a variation of average solar irradiance ($\mathbf{I}_{S.av}$), input power ($\mathbf{P}_{i.av}$), and input heat ($\mathbf{Q}_{i.av}$) over a time. For the highest value reached, the $\mathbf{I}_{S.av}$ has 605.2 W/m^2, $\mathbf{P}_{i.av}$ has 484.2 W, $\mathbf{Q}_{i.av}$has 242.2, both at the same time (12:30 P.M.). This clearly showed a direct relationship between $\mathbf{I}_{S.av}$, $\mathbf{P}_{i.av}$, and $\mathbf{Q}_{i.av}$, demonstrating the effect of environmental factors on module performance.

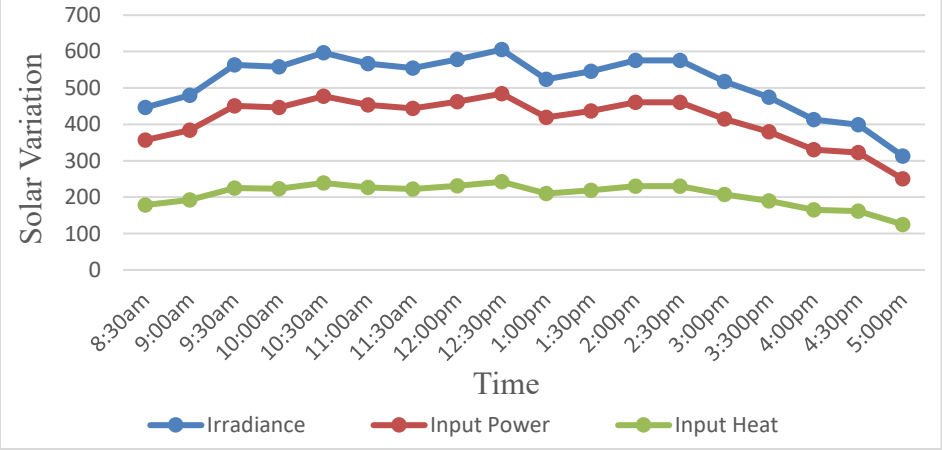


Figure 3.2Variation of solar input power and irradiance over a time

Figure 3.3 presents an average solar output power under two cooling techniques over a time. Forced air-cooling module showed a higher output power ($\mathbf{P}_{o.av_f}$), which reached 37.86 W at 11:30 am, than that of natural air-cooling ($\mathbf{P}_{o.av_n}$), which reached 32.88 W at 10:00 am. Compared to natural air-cooling control module, the forced air-cooling module has more improved output power.

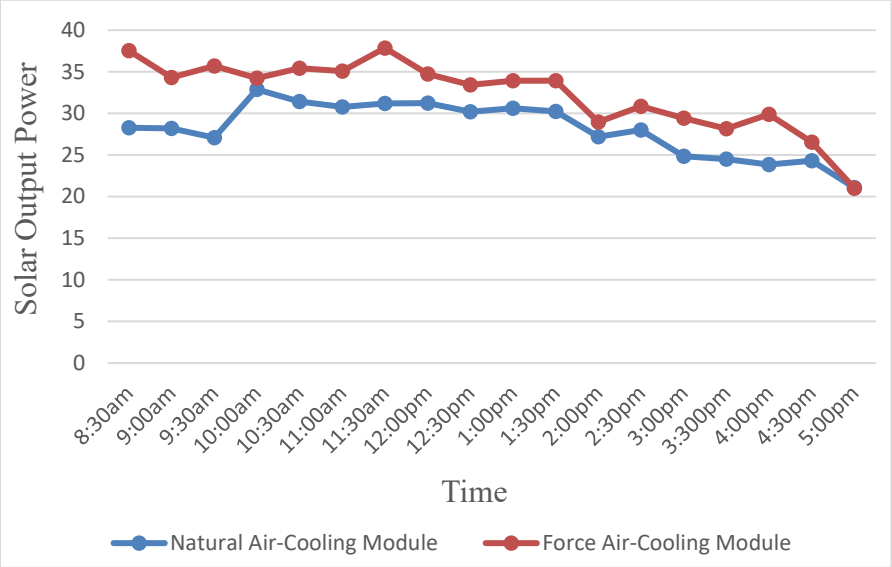


Figure 3.3 Solar output power of two different cooling modules over the time

Figure 3.4 presents an average solar output heat under two cooling techniques over a time. Natural air-cooling module showed a higher output heat ($\mathbf{Q}_{o.av_n}$), which reached 74.86 W at 10:30 am, than that of forced air-cooling ($\mathbf{Q}_{o.av_f}$), which reached 59.52 W at 40:00 pm. Compared to forced air-cooling control module, the natural air-cooling module has more improved output heat.

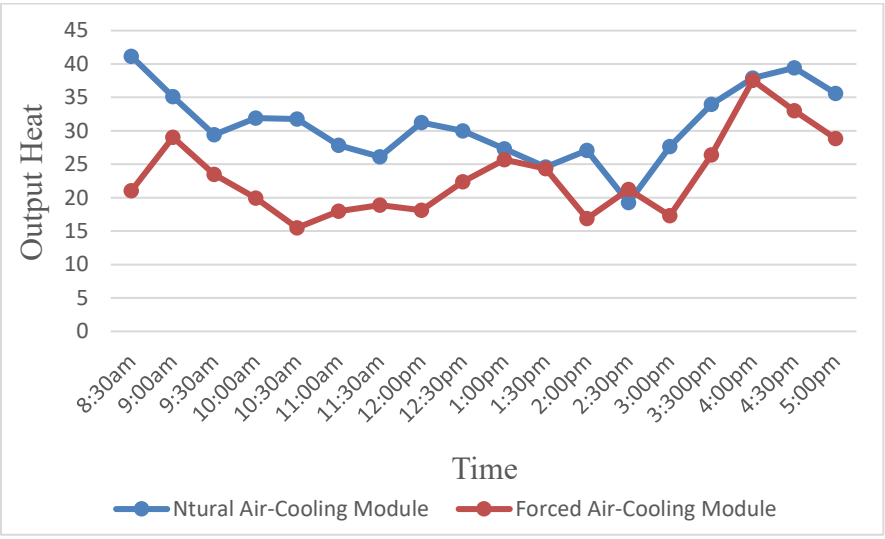


Figure3.4 Solar output heat of two different cooling modules over the time

3.4 Electrical Performance Efficiency

Table CElectrical and thermal performance efficiency of natural and forced air-cooling module

Time	Natural Air-Cooling Module		Forced Air-Cooling Module	
	Electrical Efficiency	Thermal Efficiency	Electrical Efficiency	Thermal Efficiency
8:30am	8.06	41.16	10.52	21.04
9:00am	7.32	35.14	8.8	29.02
9:30am	6.04	29.4	7.78	23.5
10:00am	7.44	31.92	7.62	19.92
10:30am	6.62	31.76	7.34	15.5
11:00am	6.8	27.82	7.66	17.98
11:30am	7.52	26.12	8.88	18.88
12:00pm	6.8	31.26	7.52	18.12
12:30pm	6.28	30.02	6.9	22.4
1:00pm	7.34	27.34	8.08	25.7
1:30pm	6.96	24.6	7.66	24.36
2:00pm	5.9	27.08	6.22	16.9
2:30pm	6.06	19.26	6.48	21.22
3:00pm	6.02	27.64	6.98	17.32
3:300pm	7.08	33.98	8.14	26.4
4:00pm	7.34	37.9	8.92	37.56
4:30pm	7.9	39.42	8.42	33
5:00pm	8.52	35.62	8.36	28.84

Figure3.5 presents an averaged comparative of electrical performance efficiency (η_{el}) between two different cooling modules (natural and forced air-cooling module) over a time. The peak

efficiency of forced air-cooling module (10.52% at 8:30 am and 8.92% at 4:00 pm) is greater than that of natural air-cooling module (7.52% at 11:30 am and 8.52% at 5:00 pm). The results occurred in the early morning and late afternoon when the solar irradiance was moderate, demonstrating the balance between cooling effectiveness and solar input.

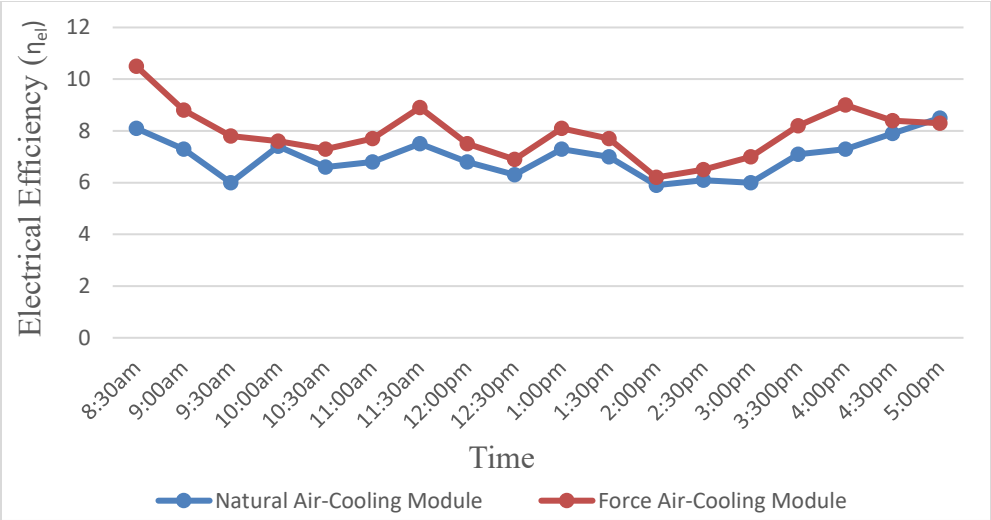


Figure 3.5Electrical efficiency comparison of two cooling modules over a time

3.5 Thermal Performance Efficiency

Figure 3.6 presents averaged comparative of thermal performance efficiency (η_{th}) between two cooling modules (natural and forced air-cooling module) over a time. The efficiency of natural air-cooling module reached 41.16% at 8:30 am, significantly showing a more heat removes from the module than that of forced air-cooling module (37.56% at 4:00 pm).

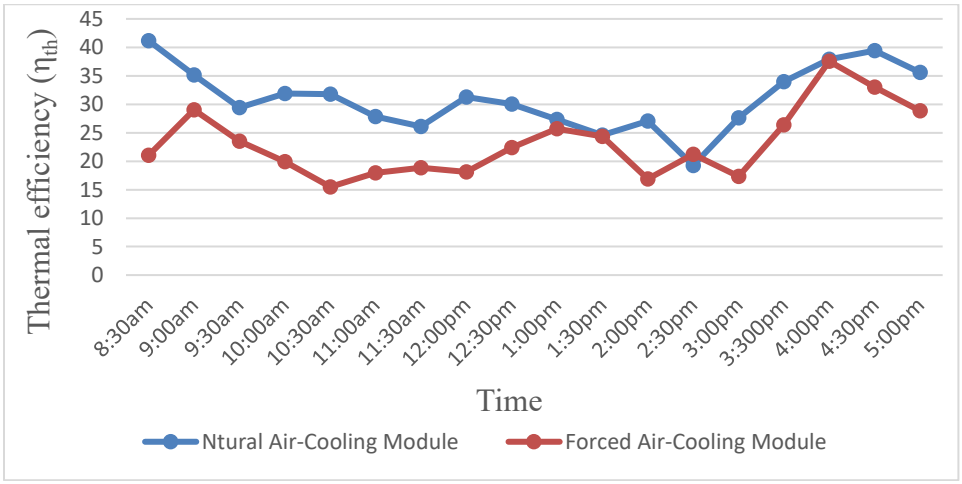


Figure 3.6Thermal efficiency comparison of two cooling modules over a time

4. Discussion

With low thermal efficiency (peaks in late afternoon due to cumulative heat removal and stable airflow), the forced air-cooling was effectively increased electrical efficiency throughout the day. Peak electrical and thermal efficiencies do not always occur simultaneously, highlighting the importance of time-of-day management in PV systems. The results confirmed that a forced air-

cooling can improve electricity generation while reducing module temperature, showing a dual benefit: improving both electrical and thermal efficiency. Therefore, forced air cooling offers a low-cost method to mitigate thermal losses and enhance PV performance in hot regions.

5. Conclusion

Good experimental setup help in data determinations and collections. Solar irradiance influence both solar input and output power and heat. Peak electrical efficiency of 9.0% and thermal efficiency of 60.1% were achieved under the experimental conditions. Forced air-cooling has significantly enhances both electrical and thermal performance of PV modules. Therefore, implementing forced air-cooling can increase energy yield and module longevity in hot climates. Future work should explore hybrid cooling methods and real-world long-term monitoring for commercial PV systems.

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