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Article

The performance evaluation of monocrystalline PV module by using water-channel cooling technique with forced convection

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Abstract: The power and efficiency of the monocrystalline PV module increase by reducing its panel temperature. It depends on the solar irradiance and the operating temperature of the PV module. Due to an increase in the operating temperature of the PV module, the efficiency decreases. As the temperature rises, the power output of the PV module also decreases. To improve the efficiency of the PV module, two different cooling techniques are investigated in this paper, i.e., the water channel cooling technique and the water-channel cooling technique accompanied with forced convection. In the water-channel cooling technique, copper pipes with serpentine and multi-inlet outlet arrangements are utilized at the backside of the mono-crystalline PV module, and the water is passed through pipes, while in water-channel cooling along with forced convection, the copper pipes with serpentine and multi-inlet outlet arrangements along with fans are employed. It is observed that the multi-inlet-outlet arrangement is more efficient as compared to the serpentine arrangement owing to the better heat transfer between the cooling media and the PV module. The experimental results demonstrate an increase in power output and efficiency realized through the reduction in operating temperature of the PV module and thus improving the open circuit voltage.

Keywords: mono-crystalline PV module; back surface cooling; photovoltaic system; forced convection; solar energy

1. Introduction

The advent of solar energy has provided the world with a renewable and sustainable source of energy to address the global energy crisis. Additionally, it is providing solutions to the other environmental issues, such as the provision of fresh water to the distant regions through solar stills. To directly harness solar energy, solar panels are being employed [1–3]. A solar panel is a device that converts solar energy into electricity known as a photovoltaic (PV) cell. This process is carried out with the help of the photovoltaic effect. The photovoltaic effect converts sunlight into voltage or current in a solar cell. In 1839 solar cells were introduced by Edmond Becquerel. In PV modules, the building blocks are solar cells, which are commonly known as solar panels [4].

The photovoltaic effect is such a phenomenon that produces current or voltage in a PV cell when exposed to the sun. This effect is applied to solar cells that convert sunlight into the desired form. The electric field is formed as a result of the formation of a p-n interface in the solar cell, as the n-type and p-type semiconductors form solar cells. In the p-n junction, an electron from the n-type silicon disperses in the p-type. When light is absorbed, free electrons are produced in the form of n, and these free electrons travel through the holes (type p). Electrons from the cathode (type n) to the anode (type p) generate electrical energy. At present, what is produced in this way is a direct current, and with an inverter, it is converted into another variable for home use [5].

The combination of PV cells is called a photovoltaic module; these PV modules form a PV system known as the PV array. Solar panels come in a number of shapes and sizes, each with its own set of characteristics that decide how they are used. These panels generate 100% renewable electricity for free. There are three main types of solar panels, all made of silicon semiconductors, and these are monocrystalline, polycrystalline, and amorphous ones. Nowadays, hybrid solar cells are also produced on a commercial basis. As far as this experimentation is concerned, only the monocrystalline PV module is discussed [6,7].

In comparison to other panels, monocrystalline solar panels are more efficient. Silicon is used in monocrystalline solar panels. In monocrystalline solar panels, all cells are made up of a single crystal. Silicon is adapted into bars and then cut into wafers in these solar cells. The electron thus generated got more space to travel; that’s why monocrystalline solar panels are more efficient. The efficiency is typically around 15%–20% for monocrystalline PV cells [8,9].

The performance parameters of PV modules are affected by environmental factors, geographical factors and the type of PV technology. The major environmental factors that affect the efficiency of photovoltaic modules are dust, wind, orientation, humidity, rain, and temperature. The major geographical factors that affect the efficiency of PV modules are solar intensity, longitude and latitude. Types of PV technology have a major effect on the efficiency of PV modules, offering distinct values.

Siecker et al. reviewed different cooling techniques such as floating concentrating cooling system, thermal and hybrid PV system cooled by water showering, thermoelectric and hybrid PV system cooled by heat submerging, thermal and hybrid PV system cooled by enforced water flow, enhancing the performance of panels by utilizing PCM, cooling by dipping panel in water, PV module cooled by translucent coating, hybrid PV system and thermal system cooled by enforced air flow. They also concluded that actual cooling of PV systems improves electrical, thermal, and overall efficiency, reducing cell degradation and extending the life of the panels. In terms of drawbacks, advantages, and techno-economic and environmental impacts, these various cooling techniques are used to address the unpleasant effect of temperature [10].

Bashir and co-workers reported an experimental analysis to test the efficiency of PV modules in the summer months and in the climate of Taxila near Pakistan’s capital. Single junction amorphous silicon, monocrystalline silicon, polycrystalline silicon, were used in the research study. Using an outdoor testing facility, the study centered on measuring module quality, output ratio, and temperature under real operating conditions. The calculated findings are comparable to previously reported data from the same source during the peak winter month. In general, the monocrystalline module had a high average module reliability, while the amorphous silicon module had a higher average output ratio. Furthermore, as the module temperature rises, the efficiency and performance ratio of the modules decreases. It was discovered that during the summer months, modules have a much higher temperature (about 20 ℃ higher) and have a lower efficiency and output ratio than during the peak months. From winter to summer, the average air temperature ranged from 18.1 ℃–38.6 ℃ [11].

In another work, Bashir and his team compared the efficiency of three photovoltaic modules, i.e., monocrystalline, polycrystalline, and single-junction amorphous silicon PV modules in Taxila, Pakistan. During the winter months, the experiment was carried out outside. For each module, the module efficiency, performance ratio and power output were determined. The effects of module temperature and solar irradiance on these parameters were also studied. Module temperature and solar irradiance had a significant influence on module parameters. When the irradiance was strong, monocrystalline and polycrystalline modules performed well; however, when the irradiance was low, performance dropped significantly. Due to its improved light absorption properties, amorphous solar modules have performed well in low irradiance conditions, resulting in a higher overall output ratio. Monocrystalline PV modules showed higher monthly average module performance and were found to be more efficient. With increasing irradiance and photovoltaic cell back surface temperature, module efficiency and performance ratio decreased. With the rise in module temperature from 22 ℃ to 33 ℃, the average module efficiency decreased by around 8.85%, 4.5%, and 26% for c-Si, p-Si, and a-Si modules, respectively. The total PR decrement for the c-Si, p-Si, and a-Si modules was 5.6%, 4.8%, and 25.8%, respectively [12].

Based on the literature review, it is concluded that no study has been carried out employing the back-surface cooling technique accompanied with forced convection. In this study, the authors present a novel approach utilizing a water-channel cooling technique along with forced convection. Two different arrangements of the water channel have been used, i.e., serpentine and multi-inlet-outlet arrangements. The experiments are carried out in the ambient conditions. The performance of the panels is compared with and without the application of back-channel water cooling technique and back-channel water channel cooling technique accompanied with forced convection.

2. Materials and methods

Experimental setup

The tests were carried out in natural conditions on the rooftop of the workshop building of COMSATS University Islamabad (Sahiwal Campus), Punjab, Pakistan (30.6506° N, 73.1158° E). There were no limitations of shadow from bushes or other homes in this area, so it was chosen. Three commercially available 50 W monocrystalline PV modules were used in the research study. The modules were positioned at an attitude of 45° from the roof. Sahiwal is placed in the northern hemisphere, so modules have been faced in the direction of the south [13,14].

$$\text{The angle of inclination (for winter)} = \text{Latitude} + 15° \quad (1)$$

$$\text{Angle of inclination (in winter) for Sahiwal} = 30.6506° + 15° = 45.6506° \quad (2)$$

The back surface cooling technique is the second studied cooling technique for the PV modules [15]. The serpentine-shaped and multi-inlet-outlet copper pipes were used behind the two PV modules, as depicted in **Figure 1**. The same experimentation was performed on two modules for multi-inlet-outlet following experimentation on serpentine-shaped arrangements of PV modules. The copper pipes were fixed tightly with the help of timber sticks for maximum touch. Thermal paste was also used to make contact between copper pipes for both techniques, as it was necessary for maximum conduction of heat. At the back of a panel, a serpentine-shaped copper pipe and 3 fans (12 V) were used to see the effects of the collaboration of two techniques; the same was utilized for the multi-inlet-outlet technique. Forced convection is preferred to avoid uncontrolled and irregular flow of air and leads to an efficiency increase of up to 14% [16,17].

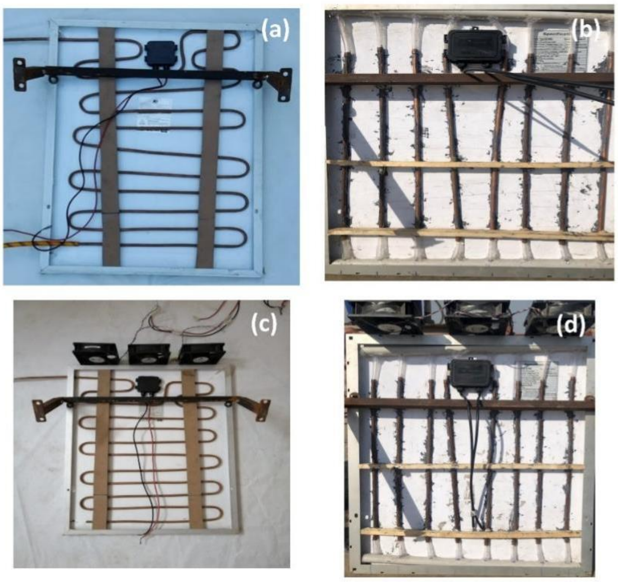


Figure 1. (a) Serpentine-shaped copper pipes on the back surface of PV module; **(b)** multi-inlet-outlet copper pipes, combined cooling techniques; **(c)** fans with serpentine-shaped copper pipes; and **(d)** fans with multi-inlet-outlet copper pipes.

The components and instruments used in the experimentation are sunlight as a source of energy, three photovoltaic modules of mono-crystalline type, panel stands, water drum, tap water as cooling medium, DC fans, DC battery, wooden sticks, PVC pipes, valves, nozzles and water channels of copper pipe (serpentine-shaped and multi-inlet-outlet).

Sunlight was used as a natural source of energy, and it is an abundantly available source of energy all over the world. Water is used for the free convection. Water flows from the back surface cooling channel by gravitational effect, so tap water is used as a cooling medium. For lower back-channel cooling of PV modules, serpentine-shaped and multi-inlet-outlet copper pipes with a 5/16’’ (8 mm) outer diameter and a wall thickness of 0.417 mm were used. The experimental arrangement is shown in **Figure 2**.

Figure 2. Experimental setup for simple PV modules and modules with cooling techniques.

Three mono-crystalline PV modules of 50 W were installed on the rooftop. One module was without any cooling technique for the comparison of results, while a back surface cooling channel was placed on the second module. On the third module, the back surface cooling channel and DC fans for the forced convection were placed. The specifications of the PV module, thermocouple thermometer, PV module analyzer, and solar surveyor are provided in **Tables 1–4**.

Table 1. Technical specifications of the PV module.

Module Model	**BS-M50**
Maximum power voltage (Vmaxp)	17.8 V
Open circuit voltage (Voc)	21.64 V
Test conditions (STC)	1000 W/m^2, AM 1.5, 25 °C
Maximum power (Pmax)	50 W
Maximum power current (Imaxp)	2.80 A
Short circuit current (Isc)	3.32 A
Tolerance	± 3%
Maximum fuse rating	8 A
Maximum system voltage	1000 VDC
Wind resistance	2400 Pa
Weight	3.8 kg
Dimension	635 × 541 × 30 mm
Application Class	A
Operating Temperature	−40 °C–85 °C

Table 2. Technical specifications of thermocouple thermometer TYPE-K DM6801A+.

General Specifications		
Display	1/2 digit large LCD, Max. display 1999	
Sampling rate	2.5 times/s	
Over range display	“1” or “−1”	
Working environment	−10 °C–50 °C, relative humidity < 80%	
Store environment	−20 °C–60 °C, relative humidity < 80%	
Battery	9 V battery	
Size	130 mm (length) × 95 mm (width) × 28 mm (height)	
Weight	Approx. 240 g (including battery)	
Accessories	Manual, Case, TP01 probe, 9V battery	
Technical Parameters		
Resolution	**Range**	**Accuracy**
0.1 °C	−50 °C to 199.9 °C	−50 °C to 199.9 °C ± (0.3% + 1 °C)
0.1 °F	−50 °F to 199.9 °F	−50 °F to 199.9 °F ± (0.3% + 1 °F)
1 °C	−50 °C to 1300 °C	−50 °C to 1000 °C ± (0.3% + 2 °C) 1000 °C to 1300 °C ± (0.6% + 2 °C)
1 °F	−50 °F to 1999 °F	−50 °F to 1000 °F ± (0.3% + 2 °F) 1000 °F to 1999 °F ± (0.6% + 2 °F)

Table 3. Technical specifications of PROVA 210 A PV module analyzer.

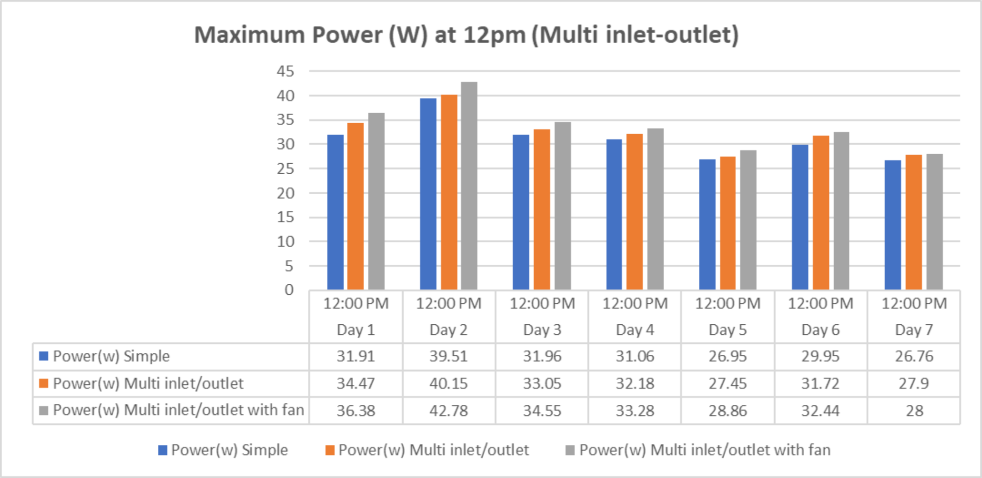
General Specifications		
Weight:	1160 g/40.9 oz (batteries are included)	
Dimensions:	257 (Length) × 155 (Width) × 57 (Height) mm, 10.1 inch (Length) × 6.1 inch (Width) × 2.2 inch (Height)	
AC-Adaptor:	AC 100 V to 240 V Input, DC 15 V/1 to 3 A Output	
Environment Storage:	−20 °C to 60 °C, 75% RH	
Environment Operation:	5 °C to 50 °C, 85% RH	
Data logging memory size	100 number of records	
Accessories:	User manual, AC Adaptor, USB Optical Cable, 3400 mAh Lithium Rechargeable Battery, CD Software, Manual Software, Carrying Bag, Kelvin Clips, 4 wire connectors.	
Measurement DC Current		
Range	**Resolution**	**Accuracy**
10 to 12 A	10 mA	±1% ± (1% of Ishort ± 0.09 A)
0.01 to 10 A	1 mA	±1% ± (1% of Ishort ± 9 mA)
Simulation DC Current		
Range	**Resolution**	**Accuracy**
10 to 12 A	10 mA	±1% ± 0.09 A
0.01 to 10 A	1 mA	±1% ± 9 mA

Table 4. Technical and general specifications of Solar Survey 200R.

General Specification	
Memory Onboard	Datasets 5000 (Survey 200R only)
Dimensions	14.8 × 8 × 3.3 cm/5.8 × 3.2 × 1.3”
Connectivity	PC USB download (Free data logger-online available) Connections wireless to PV150/PV200/PV210/Solar Utility-Pro (range c. 30 m/100 ft.) Frequency 433 MHz (Rest of World)/915 MHz (US)
Auto Power Down	Unless in transmit mode (After 2 min)
Sample Rate	1 to 60 min (user definable)
Weight	0.25 kg/0.6 lb
Technical Specifications	
Irradiance	
Resolution	1 W/m^2 or 1 Btu/hr-ft^2
Measurement	100 to 1250 W/m^2 or 30 to 400 Btu/hr-ft^2
Display	100 to 1500 W/m^2 or 30 to 500 Btu/hr-ft^2
Temperature	
Resolution	1°
Measurement	−30 ℃ up to +125 ℃
Display	−30 ℃ up to +125 ℃
Compass Bearing	
Resolution	1°
Measurement	0° up to 360°
Display	0° up to 360°
Inclinometer	
Resolution	1°
Measurement	0° up to 90°
Display	0° up to 90°

3. Results and discussion

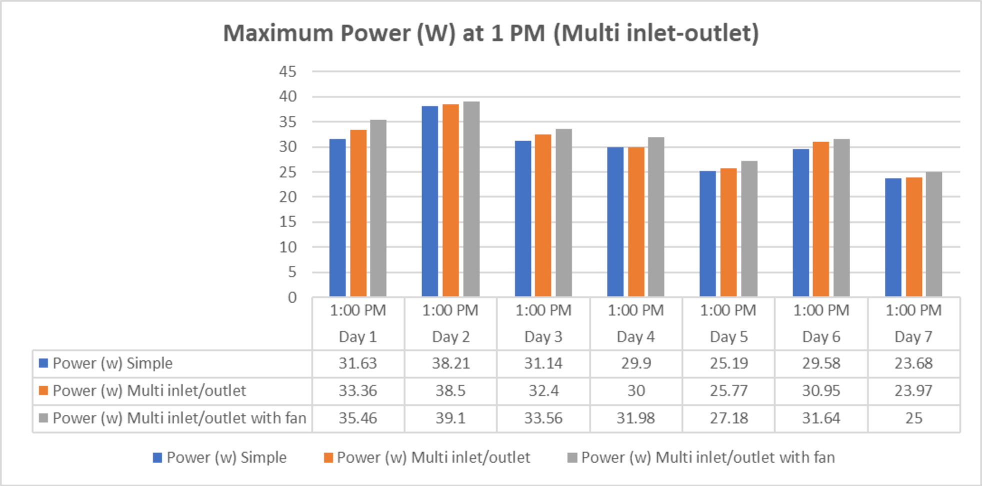
As far as the results of the research study are concerned, two readings at 12 PM and 1 PM are taken into account, keeping in view the fact that maximum irradiance is observed for these timings. It has been reported that almost 70% of the power falling upon the PV module is transformed into heat; however, the application of the hybrid cooling technique led to the increase in the power output [18]. The power output can be calculated from the product of output voltage and current. The maximum power output of the PV module increased as shown in **Figures 3** and **4,** as well as efficiency also increased as shown in **Figures 5** and **6** after the application of the cooling technique. At 12 PM the maximum power is 42.78 W (**Figure 3**) on day 2, and the maximum efficiency is 14.84% (**Figure 5**) on day 6. Similarly, at 1 PM the maximum power is 39.1 W (**Figure 4**) on day 2, and maximum efficiency is 15.76% (**Figure 6**) on day 2. The better performances are attributed to the fact that effective heat transfer takes place between the cooling media and the PV module, improving the overall performance.



	12:00 PM Day 1	12:00 PM Day 2	12:00 PM Day 3	12:00 PM Day 4	12:00 PM Day 5	12:00 PM Day 6	12:00 PM Day 7
🟦 Power(w) Simple	31.91	39.51	31.96	31.06	26.95	29.95	26.76
🟧 Power(w) Multi inlet/outlet	34.47	40.15	33.05	32.18	27.45	31.72	27.9
▨ Power(w) Multi inlet/outlet with fan	36.38	42.78	34.55	33.28	28.86	32.44	28

Figure 3. Maximum power comparison for multi-inlet-outlet at 12 PM.

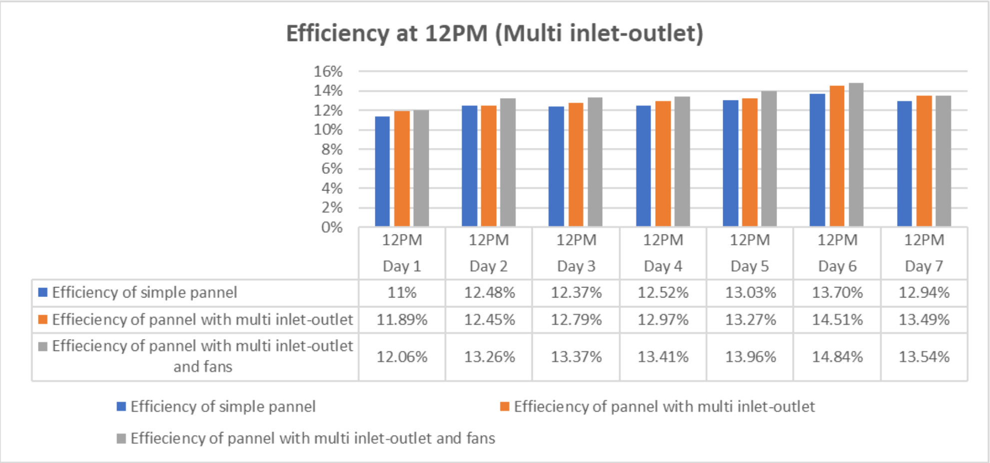
Maximum power is 39.1 W at 1 PM on day 2 as shown in **Figure 4**.



	1:00 PM Day 1	1:00 PM Day 2	1:00 PM Day 3	1:00 PM Day 4	1:00 PM Day 5	1:00 PM Day 6	1:00 PM Day 7
🟦 Power (w) Simple	31.63	38.21	31.14	29.9	25.19	29.58	23.68
🟧 Power (w) Multi inlet/outlet	33.36	38.5	32.4	30	25.77	30.95	23.97
▨ Power (w) Multi inlet/outlet with fan	35.46	39.1	33.56	31.98	27.18	31.64	25

Figure 4. Maximum power comparison for multi-inlet-outlet at 1 PM.

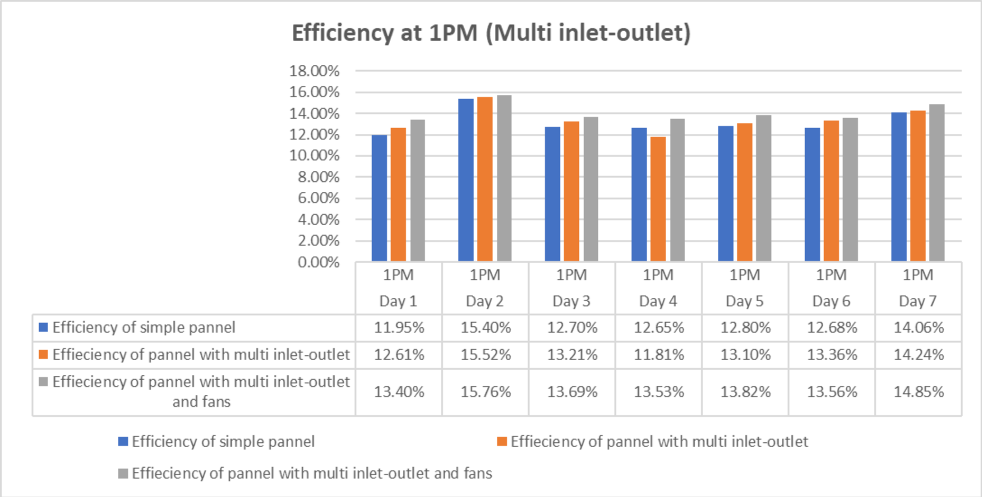
Maximum efficiency is 14.84% at 12 PM on day 6 as shown in **Figure 5**.



	12PM Day 1	12PM Day 2	12PM Day 3	12PM Day 4	12PM Day 5	12PM Day 6	12PM Day 7
🟦 Efficiency of simple pannel	11%	12.48%	12.37%	12.52%	13.03%	13.70%	12.94%
🟧 Effieciency of pannel with multi inlet-outlet	11.89%	12.45%	12.79%	12.97%	13.27%	14.51%	13.49%
▨ Effieciency of pannel with multi inlet-outlet and fans	12.06%	13.26%	13.37%	13.41%	13.96%	14.84%	13.54%

Figure 5. Efficiency comparison for multi-inlet-outlet at 12 PM.

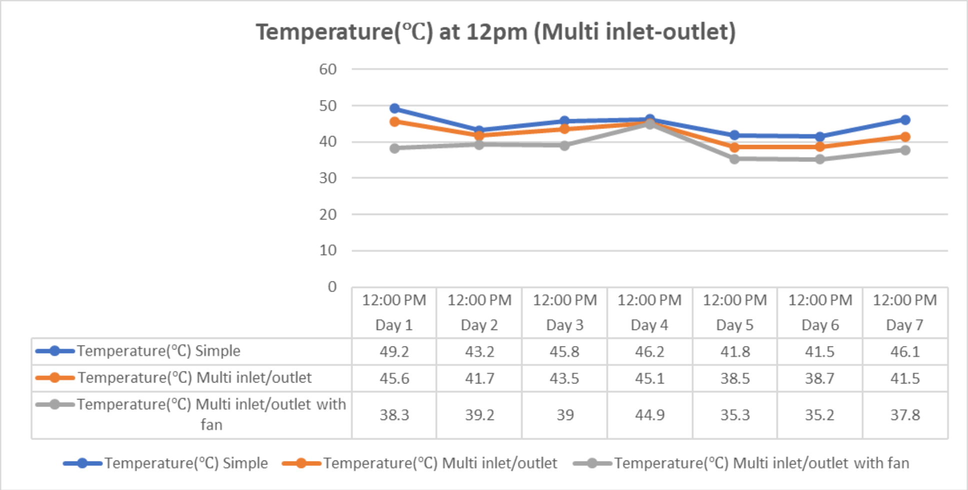
Maximum efficiency is 15.76% at 1 PM on day 2 as shown in **Figure 6**.



	1PM Day 1	1PM Day 2	1PM Day 3	1PM Day 4	1PM Day 5	1PM Day 6	1PM Day 7
■ Efficiency of simple pannel	11.95%	15.40%	12.70%	12.65%	12.80%	12.68%	14.06%
■ Effieciency of pannel with multi inlet-outlet	12.61%	15.52%	13.21%	11.81%	13.10%	13.36%	14.24%
■ Effieciency of pannel with multi inlet-outlet and fans	13.40%	15.76%	13.69%	13.53%	13.82%	13.56%	14.85%

Figure 6. Efficiency comparison for multi-inlet-outlet at 1 PM.

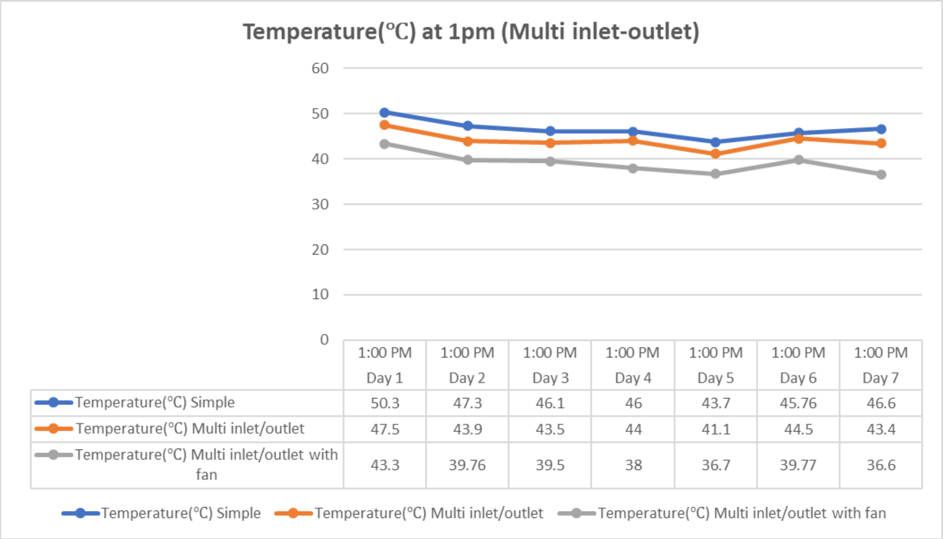
The variation in panel temperature and irradiance is depicted in **Figures 7–11**. It can be observed that there was interference of the clouds during the study that led to the variation of irradiance and consequently to the change in panel temperatures. It can be clearly observed that the application of the cooling technique significantly decreased the panel temperatures. The maximum temperature is 44.9 ℃ at 12 PM on day 4 as depicted in **Figure 7**.



	12:00 PM Day 1	12:00 PM Day 2	12:00 PM Day 3	12:00 PM Day 4	12:00 PM Day 5	12:00 PM Day 6	12:00 PM Day 7
Temperature(°C) Simple	49.2	43.2	45.8	46.2	41.8	41.5	46.1
Temperature(°C) Multi inlet/outlet	45.6	41.7	43.5	45.1	38.5	38.7	41.5
Temperature(°C) Multi inlet/outlet with fan	38.3	39.2	39	44.9	35.3	35.2	37.8

Figure 7. Panel temperature comparison for multi-inlet-outlet at 12 PM.

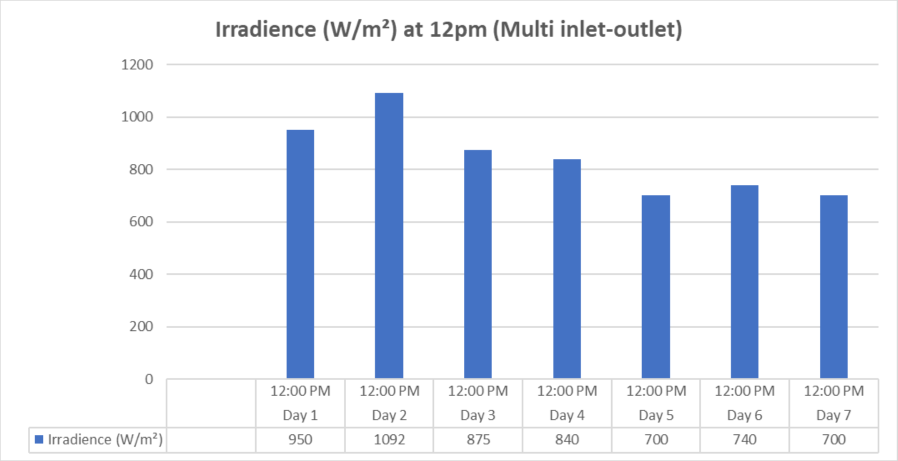
The maximum temperature is 43.3 ℃ at 1 PM on day 1 as exhibited in **Figure 8**.



	1:00 PM Day 1	1:00 PM Day 2	1:00 PM Day 3	1:00 PM Day 4	1:00 PM Day 5	1:00 PM Day 6	1:00 PM Day 7
Temperature(℃) Simple	50.3	47.3	46.1	46	43.7	45.76	46.6
Temperature(℃) Multi inlet/outlet	47.5	43.9	43.5	44	41.1	44.5	43.4
Temperature(℃) Multi inlet/outlet with fan	43.3	39.76	39.5	38	36.7	39.77	36.6

Figure 8. Panel temperature comparison for multi-inlet-outlet at 1 PM.

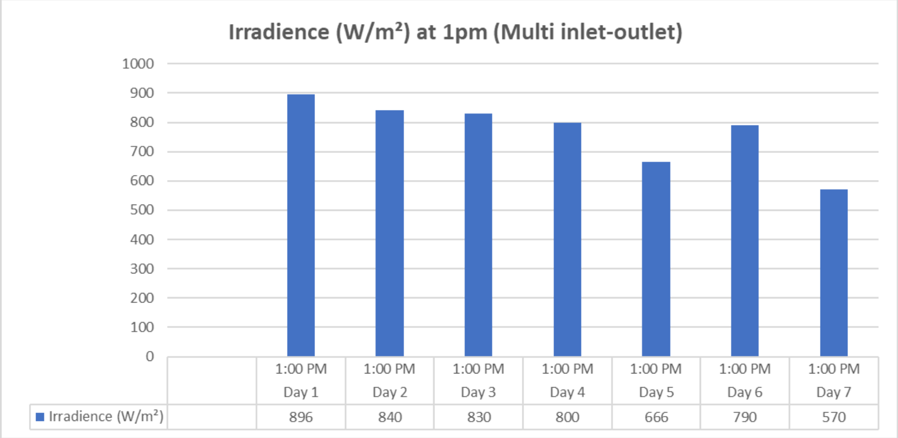
Maximum irradiance is 1092 W/m^2 at 12 PM on day 2 as demonstrated in **Figure 9**.



	12:00 PM Day 1	12:00 PM Day 2	12:00 PM Day 3	12:00 PM Day 4	12:00 PM Day 5	12:00 PM Day 6	12:00 PM Day 7
■ Irradience (W/m²)	950	1092	875	840	700	740	700

Figure 9. Irradiance comparison for multi-inlet-outlet at 12 PM.

Maximum irradiance is 896 W/m^2 at 1 PM on day 1 as shown in **Figure 10**.



	1:00 PM Day 1	1:00 PM Day 2	1:00 PM Day 3	1:00 PM Day 4	1:00 PM Day 5	1:00 PM Day 6	1:00 PM Day 7
■ Irradience (W/m²)	896	840	830	800	666	790	570

Figure 10. Irradiance comparison for multi-inlet-outlet at 1 PM.

The variation in the temperature of the panel also causes the change in open circuit voltage as depicted in **Figures 11** and **12**. This can be ascribed to the dependence of the properties of semiconductor on the temperature. The rise in temperature leads to the higher saturation current which ultimately affects the open circuit voltage by reducing it [19]. Maximum open circuit voltage is 20.89 V at 12 PM on day 2 as shown in **Figure 11**.

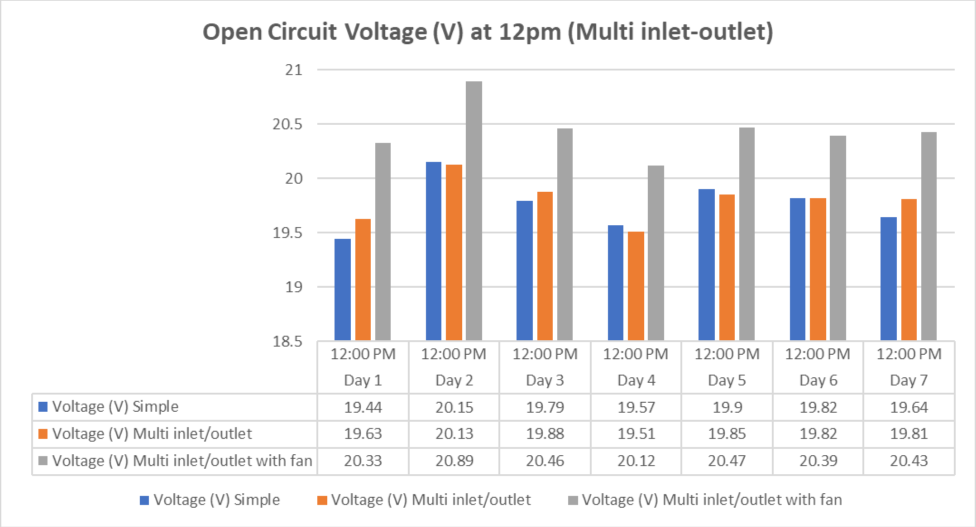


Figure 11. Open circuit voltage comparison for multi-inlet-outlet at 12 PM.

Maximum open circuit voltage is 21.1 V at 1 PM on day 2 as observed in **Figure 12**.

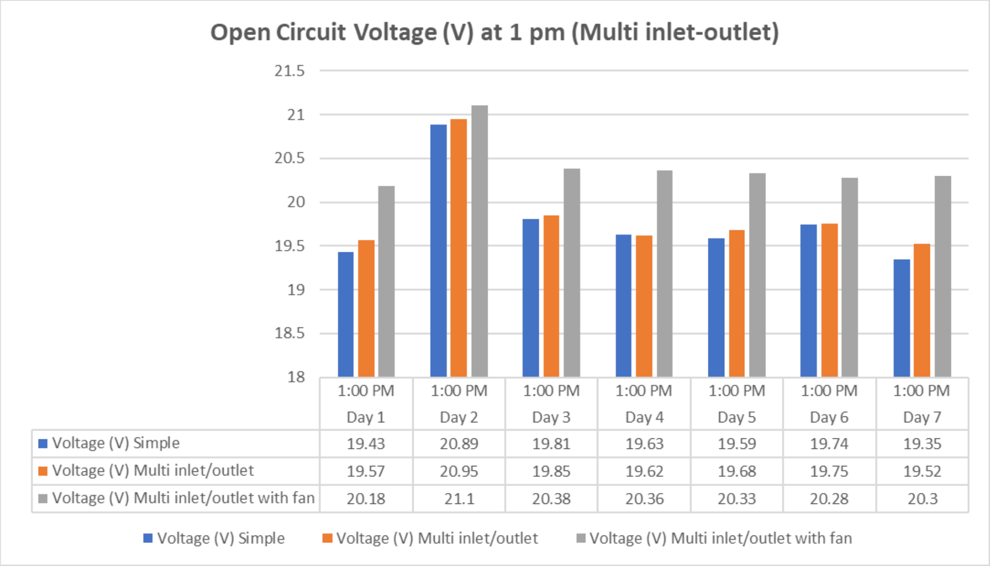
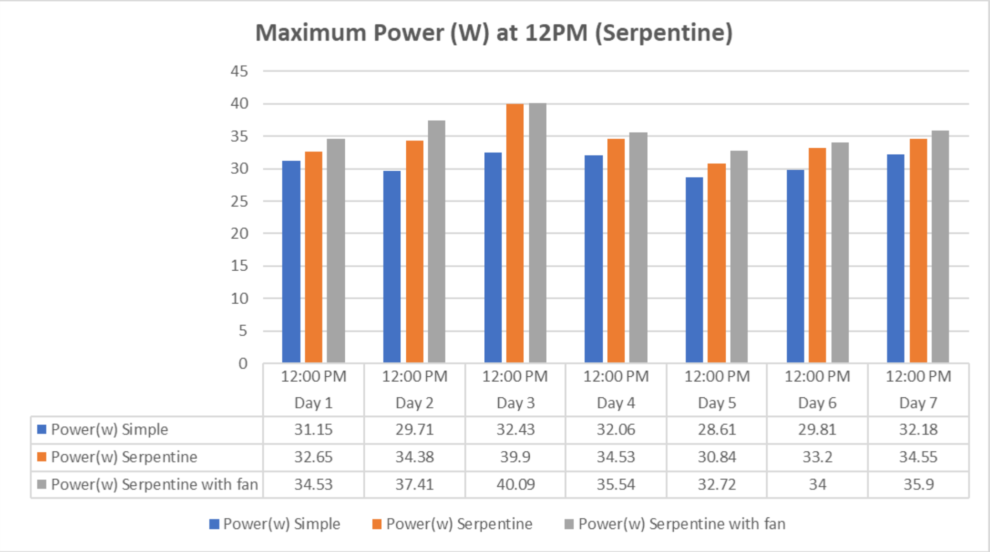


Figure 12. Open circuit voltage comparison for multi-inlet-outlet at 1 PM.

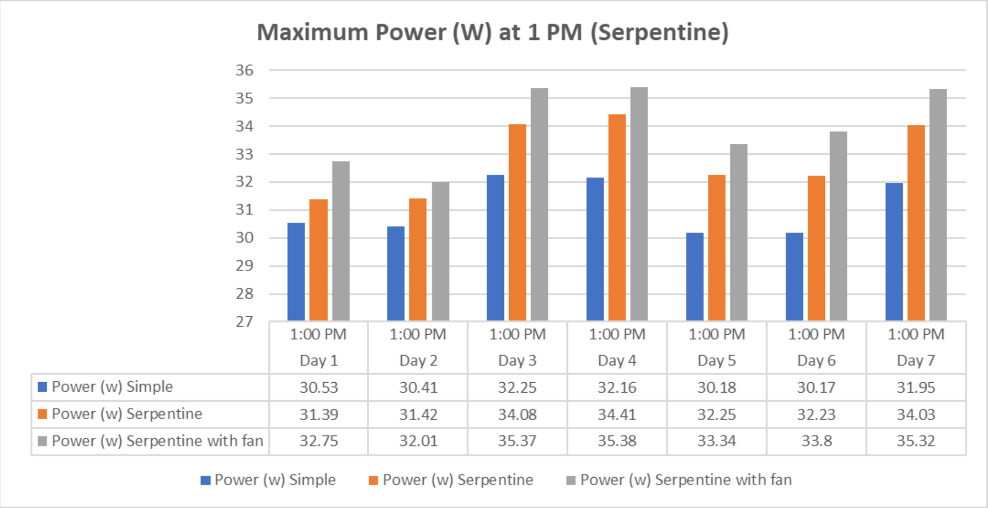
The same set of parameters is investigated for serpentine arrangement as discussed above. The maximum power output of the PV module increased as shown in **Figures 13** and **14,** and efficiency also increased, as shown in **Figures 15** and **16,** owing to the application of the cooling technique. At 12 PM, the maximum power is 40.09 W on day 3, and maximum efficiency is 14.23% on day 2. Similarly, at 1 PM the maximum power is 35.38 W on day 4 and maximum efficiency is 14.09% on day 1. Maximum power at 12 PM is 40.09 W on day 3, as shown in **Figure 13**.



	12:00 PM Day 1	12:00 PM Day 2	12:00 PM Day 3	12:00 PM Day 4	12:00 PM Day 5	12:00 PM Day 6	12:00 PM Day 7
■ Power(w) Simple	31.15	29.71	32.43	32.06	28.61	29.81	32.18
■ Power(w) Serpentine	32.65	34.38	39.9	34.53	30.84	33.2	34.55
■ Power(w) Serpentine with fan	34.53	37.41	40.09	35.54	32.72	34	35.9

Figure 13. Maximum power comparison for serpentine at 12 PM.

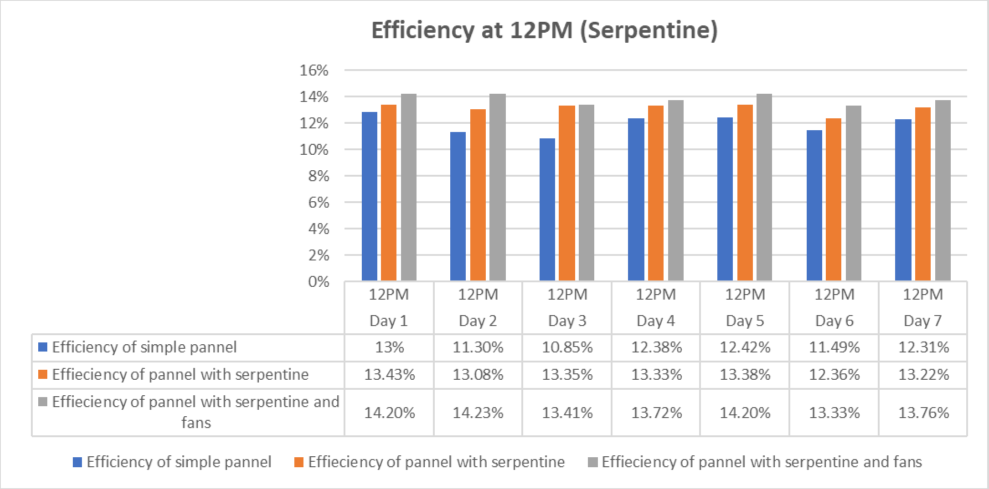
Maximum power is 35.38 W on day 4 at 1 PM as shown in **Figure 14**.



	1:00 PM Day 1	1:00 PM Day 2	1:00 PM Day 3	1:00 PM Day 4	1:00 PM Day 5	1:00 PM Day 6	1:00 PM Day 7
■ Power (w) Simple	30.53	30.41	32.25	32.16	30.18	30.17	31.95
■ Power (w) Serpentine	31.39	31.42	34.08	34.41	32.25	32.23	34.03
■ Power (w) Serpentine with fan	32.75	32.01	35.37	35.38	33.34	33.8	35.32

Figure 14. Maximum power comparison for serpentine at 1 PM.

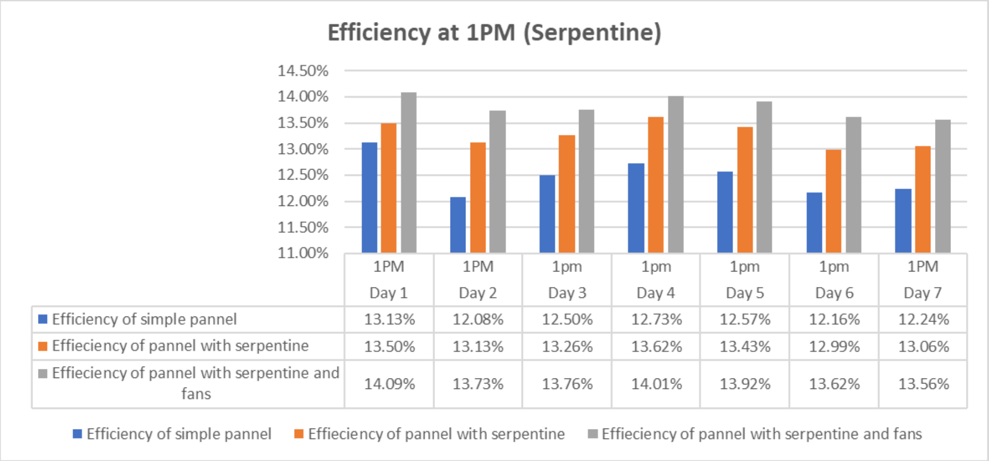
Maximum efficiency is 14.23% at 12 PM on day 2 as shown in **Figure 15**.



	12PM Day 1	12PM Day 2	12PM Day 3	12PM Day 4	12PM Day 5	12PM Day 6	12PM Day 7
■ Efficiency of simple pannel	13%	11.30%	10.85%	12.38%	12.42%	11.49%	12.31%
■ Effieciency of pannel with serpentine	13.43%	13.08%	13.35%	13.33%	13.38%	12.36%	13.22%
■ Effieciency of pannel with serpentine and fans	14.20%	14.23%	13.41%	13.72%	14.20%	13.33%	13.76%

Figure 15. Efficiency comparison for serpentine at 12 PM.

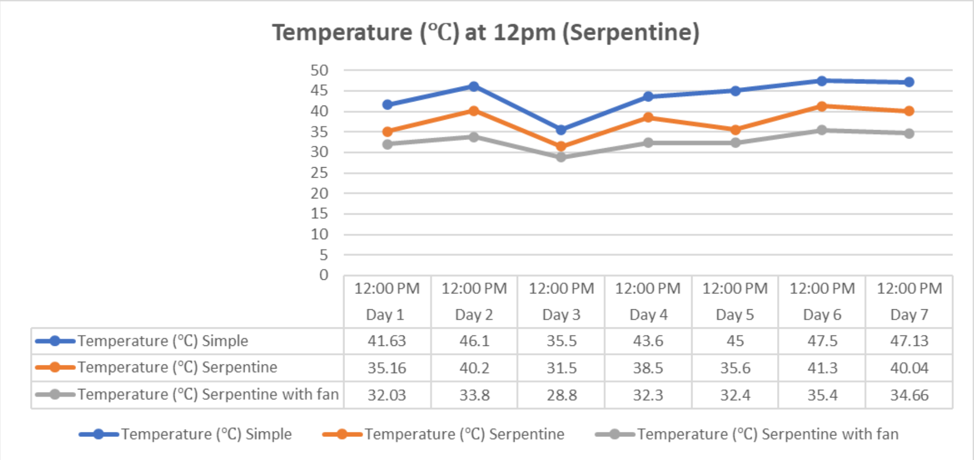
Maximum efficiency is 14.09% at 1 PM on day 1 as shown in **Figure 16**.



	1PM Day 1	1PM Day 2	1pm Day 3	1pm Day 4	1pm Day 5	1pm Day 6	1PM Day 7
■ Efficiency of simple pannel	13.13%	12.08%	12.50%	12.73%	12.57%	12.16%	12.24%
■ Effieciency of pannel with serpentine	13.50%	13.13%	13.26%	13.62%	13.43%	12.99%	13.06%
■ Effieciency of pannel with serpentine and fans	14.09%	13.73%	13.76%	14.01%	13.92%	13.62%	13.56%

Figure 16. Efficiency comparison for serpentine at 1 PM.

The minimum temperature is 28.8 °C at 12 PM on day 3 as demonstrated in **Figure 17**.



	12:00 PM Day 1	12:00 PM Day 2	12:00 PM Day 3	12:00 PM Day 4	12:00 PM Day 5	12:00 PM Day 6	12:00 PM Day 7
—●— Temperature (°C) Simple	41.63	46.1	35.5	43.6	45	47.5	47.13
—●— Temperature (°C) Serpentine	35.16	40.2	31.5	38.5	35.6	41.3	40.04
—●— Temperature (°C) Serpentine with fan	32.03	33.8	28.8	32.3	32.4	35.4	34.66

Figure 17. Panel temperature comparison for serpentine at 12 PM.

The minimum temperature is 32.3 ℃ at 1 PM on day 1 as depicted in **Figure 18**.

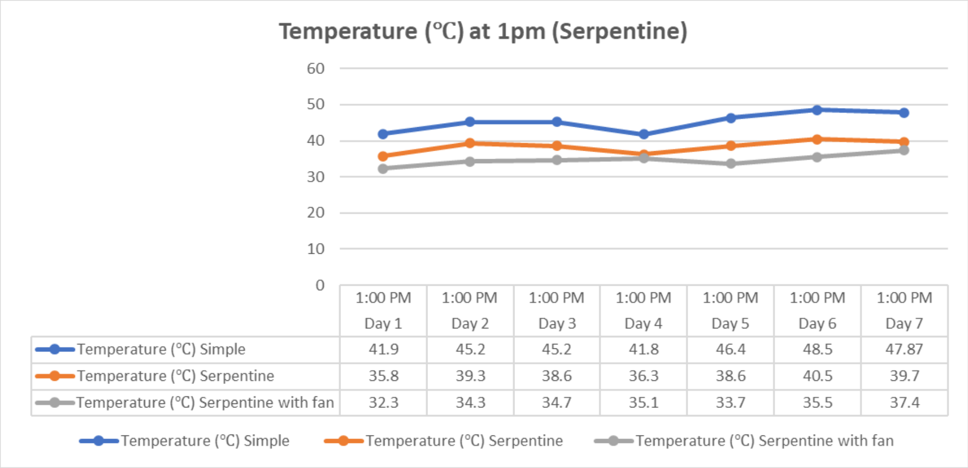


Figure 18. Panel temperature comparison for serpentine at 1 PM.

Maximum irradiance is 1012 W/m^2 at 12 PM on day 3 as observed in **Figure 19**.

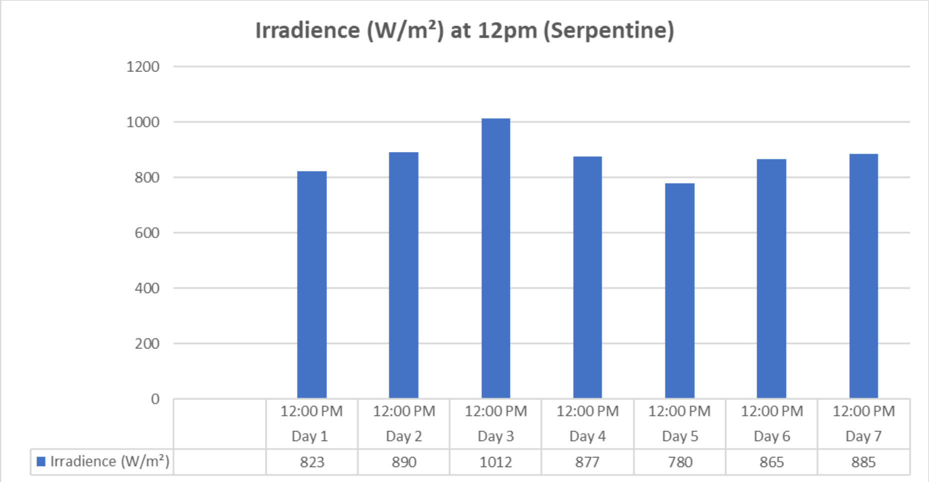


Figure 19. Irradiance comparison for serpentine at 12 PM.

Maximum irradiance is 882 W/m^2 at 1 PM on day 7 as shown in **Figure 20**.

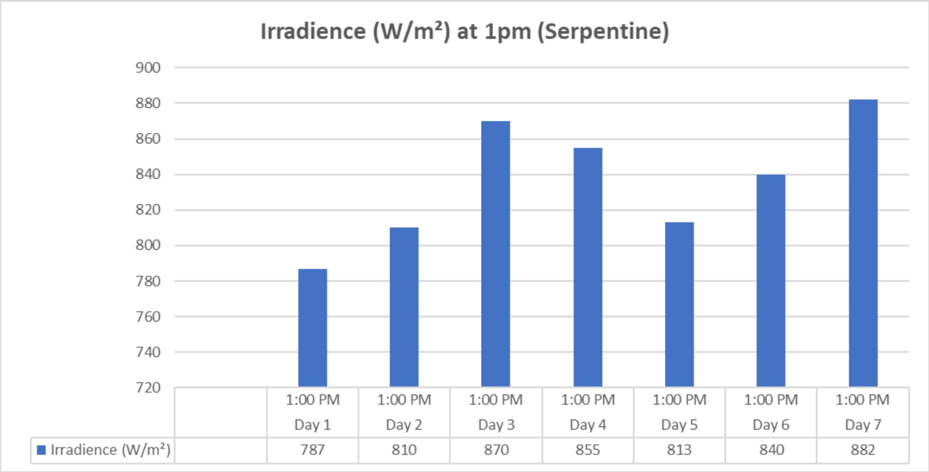
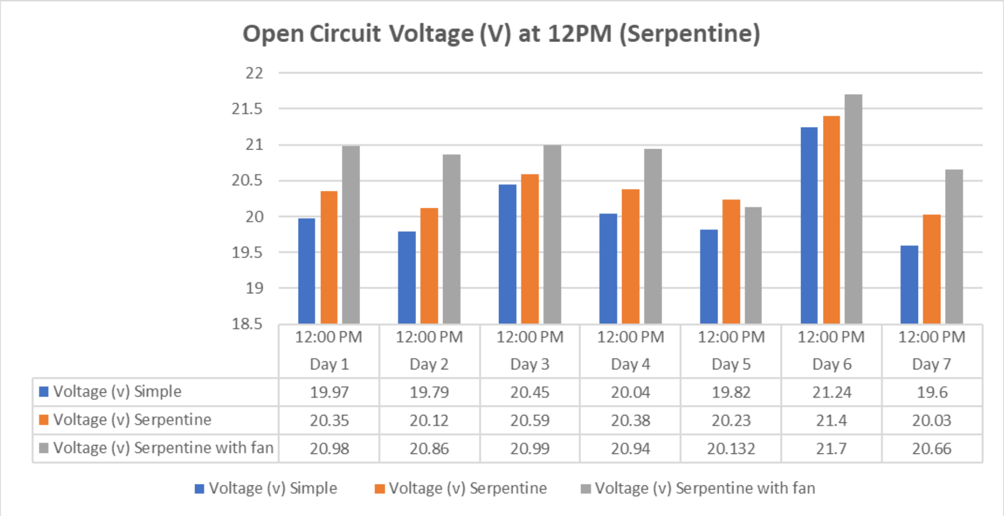


Figure 20. Irradiance comparison for serpentine at 1 PM.

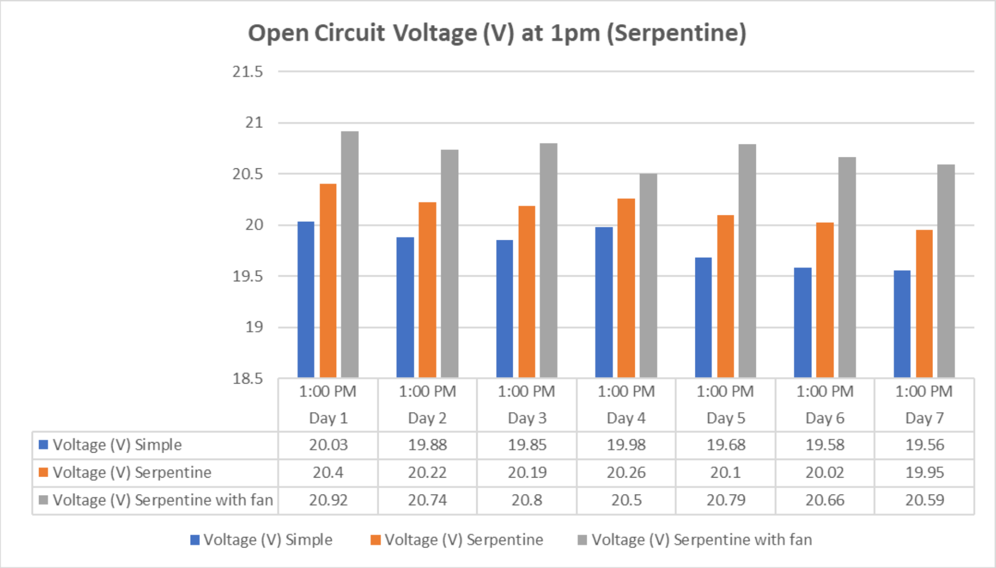
Maximum open circuit voltage is 21.7 V at 12 PM on day 6 as shown in **Figure 21**.



	12:00 PM Day 1	12:00 PM Day 2	12:00 PM Day 3	12:00 PM Day 4	12:00 PM Day 5	12:00 PM Day 6	12:00 PM Day 7
■ Voltage (v) Simple	19.97	19.79	20.45	20.04	19.82	21.24	19.6
■ Voltage (v) Serpentine	20.35	20.12	20.59	20.38	20.23	21.4	20.03
■ Voltage (v) Serpentine with fan	20.98	20.86	20.99	20.94	20.132	21.7	20.66

Figure 21. Open circuit voltage comparison for serpentine at 12 PM.

Maximum open circuit voltage is 20.92 V at 1 PM on day 1 as depicted in **Figure 22**.



	1:00 PM Day 1	1:00 PM Day 2	1:00 PM Day 3	1:00 PM Day 4	1:00 PM Day 5	1:00 PM Day 6	1:00 PM Day 7
■ Voltage (V) Simple	20.03	19.88	19.85	19.98	19.68	19.58	19.56
■ Voltage (V) Serpentine	20.4	20.22	20.19	20.26	20.1	20.02	19.95
■ Voltage (V) Serpentine with fan	20.92	20.74	20.8	20.5	20.79	20.66	20.59

Figure 22. Open circuit voltage comparison for serpentine at 1 PM.

The nature of the solar irradiance is stochastic and undergoes changes. In this backdrop, it is difficult to perform multiple measurements for different arrangements. When measurements are performed, uncertainty affects the experimental results. The independent parameters for the study include current, solar irradiance, voltage, and panel temperature. Different instruments are employed to measure these parameters. It can be noticed that the uncertainty values are quite close for each arrangement. This is ascribed to the measurements taken by the same instrument. The uncertainty analysis is provided in **Table 5** for the instruments used in this experimental study.

Table 5. Overall average fractional uncertainty.

Parameter	Unit	Serpentine	Multi Inlet	Overall Average Fractional Uncertainty
Solar Irradiance	W/m^2	0.001	0.001	0.001
Panel Temperature	C	0.003	0.003	0.003
Improvement in short circuit current	mA	0.055	0.029	0.042
Improvement in open circuit voltage	V	0.022	0.029	0.025
Improvement in fill factor	%	0.411	0.420	0.415
Improvement in power	%W	0.224	0.228	0.226

4. Conclusion

The effect of temperature increase on the performance of the monocrystalline photovoltaic module was investigated. Three mono-crystalline PV modules were placed on the rooftop workshop, mechanical department, COMSATS Sahiwal, Punjab, Pakistan, for 14 consecutive days. Two different techniques, water-channel cooling and water-channel cooling along with forced convection, were employed.

- The results demonstrate that water-channel cooling along with the forced convection technique exhibited higher maximum output power and efficiency as compared to simple and water-channel cooling techniques.
- For serpentine shape, the maximum power output of the simple module is 29.71 W, 34.38 W for the water-channel cooling technique, and 37.41 W for the water-channel cooling technique with forced convection, respectively, is observed on day 2. This is ascribed to the effectiveness of the combined cooling techniques.
- For the multi-inlet-outlet shape, the maximum power output of the simple module is 39.51 W, 40.15 W for the water-channel cooling technique, and 42.78 W is noted for the water-channel cooling technique with forced convection.
- After applying cooling techniques, panel temperature decreases up to 15 ℃, open circuit voltage increases up to 2 V, and efficiency increases up to 4%–5%. By comparison, it is concluded that the multi-inlet-outlet water channel cooling technique is better than the serpentine-shaped water channel cooling technique because maximum power is obtained by that technique. In the future, the incorporation of nanoparticles in the cooling media can be investigated.

Author contributions: Conceptualization, MTA; methodology, TR; software, MAA; validation, NH; writing—review and editing, MK; formal analysis, MSN; investigation, MRA; data curation, ZA; writing—original draft preparation, EUH; writing—review and editing, SKHS; supervision, MTA; project administration, MTA. All authors have read and agreed to the published version of the manuscript.

Conflict of interest: The authors declare no conflict of interest.

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