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Article

Photovoltaic backside cooling using the space inside a conventional frame (IPCOSY)

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ABSTRACT

Inefficiencies present in solar cells result in most of the absorbed energy being converted into heat, causing an increase in cell temperature, which leads to a further reduction in efficiency. Various cooling technologies can be found in the literature; however, these all come with their own challenges. In this research, we have designed a Photovoltaic (PV) panel that incorporates backside water cooling by creating a water chamber in the empty space inside the Aluminium frame. This panel was termed IPCoSy (Innovative Photovoltaic Cooling System). It was tested against a conventional cooling system that allowed water to drain when the cooling is switched off and a non-cooled control panel, and the results show that, even without any flow, a daily energy gain of about 3% is possible. When a controlled flow was introduced, gains of up to 10% were achieved. These gains can be further increased when IPCoSy is installed in ideal scenarios such as reverse osmosis plants, floating PV installations, or areas requiring water heating. Therefore, this research presents a new photovoltaic panel incorporating a water chamber designed for hot climate conditions.

1. Introduction

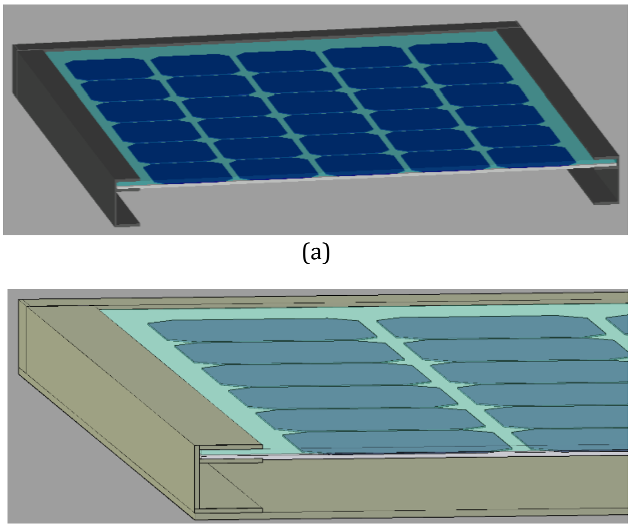
Photovoltaic (PV) cells absorb approximately 80% of the incident light however, conversion inefficiencies of solar cells result in only a portion of incident light energy being converted to electrical energy [1]. A photovoltaic (PV) module installed outside can have solar cells reaching a temperature up to 40℃ above ambient temperature [2]. According to the law of conservation of energy, if a module's temperature is rising, this means that some of the solar energy is being converted to heat energy instead of electrical energy. This is due to the fact that solar cells are only using part of the solar spectrum to generate electricity. Typical conversion efficiencies for single junction solar cells range between 6% to 25% depending on the material technology used [2]. An increase in solar cell temperature will result in a drop in the conversion efficiency of the module [3]. Therefore, the effect of temperature contributes to solar modules operating at lower efficiencies. When a crystalline silicon cell's temperature increases by 1 degree, the module's conversion efficiency reduces in steps by 0.08% while the output power is reduced by up to 0.65%. Furthermore, the fill factor also decreases at a rate of 0.2%/K [4]. In hot regions, PV modules can reach temperatures of up to 80℃ while in tropical environments, the temperature can rise beyond the operating range of the modules [5]. This not only results in a high-efficiency loss but also accelerates the module's degradation.

Boussaid et al. [6] carried out a study showing that degradation due to temperature is of a higher magnitude in photovoltaic modules in open-circuit conditions. This effect occurs because in open circuit conditions, charges only have the possibility of recombination through Shockley-Read-Hall (SRH) and Auger, both of which result in an increase in temperature in the cell material. This increase in temperature results in non-elastic expansion and contraction cycles of the crystal lattice, which in the long run, result in permanent cell degradation [6]. Therefore, cooling is one of the key solutions to consider when optimizing a PV system design. Cooling not only improves the efficiency of the panel but also prolongs its life. Ongoing research resulted in various cooling technologies being implemented with the aim of cooling photovoltaic modules. The heat from PV modules can be extracted either actively, for example, using water cooling, forced air cooling, thermoelectric cooling, and heat pipes, or passively such as using Phase Change Materials (PCMs), heat sinks [7], and natural air cooling [2]. The adequate cooling technology depends on the system's operating conditions, and capital and maintenance costs must be kept to a minimum in order to make such a system economically feasible. Cooling is usually applied either to the front side of a PV module, the backside, or both. A study [8] implemented a front-side pulsed water-cooling system that achieved a maximum increase in electrical efficiency of 2.4%. This system is however, utilizing an existing water flow, and therefore, no extra pump power was considered. A possible disadvantage of cooling on the front-side is that the cooling system can cause shading, and it can also stain the glass with lime-scale or salt (if using seawater) [7]. Another system combines a backside water spraying cooling system with a solar water heater. The cooling system alone increased the electrical efficiency by 1.4%, however, when acting as a pre-heater to a solar water heater, the overall system efficiency was 61.7% [9]. A cooling system involving a flow of water through a configuration of PVC pipes installed at the back of the PV module achieved a maximum increase in power output of 5 to 13% [10]. However, this study does not factor in pumping power and water consumption. Furthermore, none of the above cooling systems address the fact that when the water cooling flow is stopped, the PV temperature in hot climates will increase again at a fast rate. Since this research has a possible application in offshore or floating PVs, only backside water-cooling was considered. The hypothesis studied in this research is that if one creates a chamber at the back of the PV modules, utilizing the existing space created by the aluminium frame, and fills this chamber with water, the added specific heat capacity will keep the modules cooler during the day thus, working more efficiently. Furthermore, a controlled flow switching is being proposed where a water flow is initiated to lower the PV module's temperature and after reaching the required low-temperature threshold, the water is stored in this chamber in contact with the back of the PV module instead of being discarded. With this setup, the PV module should take longer to reach the high-temperature threshold, and thus, the pump switching frequency is reduced, prolonging the lifetime of the pump and decreasing the power consumption. When the high-temperature threshold is reached, flow is initiated and the water chamber is filled with cold water while the hot water is pushed out. This hot water can be used as pre-heated water for water heaters, can be discarded if in a floating installation, or recycled in a large water reservoir. The aim of this study is to analyze the effectiveness of a newly designed cooling system, termed IPCoSy, in keeping photovoltaic operating temperatures at optimum conditions.

2. Materials and Methods

2.1 Prototype Design

Initially, two different prototypes were designed and implemented in order to test the above hypothesis. The first prototype involved the modification of an existing photovoltaic module consisting of a top glass cover, polymer back sheet, and an aluminium frame. Small 5W ET solar panels were used in order to facilitate in-house prototyping. The dimensions of the active area were 30.5cm by 12.5cm, while the dimensions of the water chamber were 38.5cm by 16cm by 2.5cm. This resulted in a volume of water of 1.54L or 40.4L per m^2 of PV active area. A cross-section of a conventional photovoltaic module can be seen in Figure 1(a). The idea of this prototype was to close the backside of the module, thus creating a closed chamber underneath, as shown in the design in Figure 1(b). In practice, this can be achieved by welding an aluminium sheet however, for the scope of this research, a 5mm Poly (methyl methacrylate) sheet was used instead. Since water would be in direct contact with the back sheet of the PV module, it was important to seal the junction box containing the electrical contacts. Therefore, the junction box was electrically insulated by pouring a liquid resin mixture inside the box and allowing it to cure.


(a)

(b)

Figure 1. Cross-sections of (a) a conventional photovoltaic module and (b) the first IPCoSy prototype with the backside completely closed

Furthermore, two Hep2O® fittings were fitted on the short sides of each module to enable the flow of water underneath the photovoltaic cells. In addition, waterproof Negative Temperature Coefficient (NTC) Thermistors were installed at the back of each PV module in order to monitor the PV cells' temperature. These three modifications are shown in Figure 2. Finally, the 5mm Poly (methyl methacrylate) sheet was attached to the back of the PV module frame using a strong sealing and bonding agent.

Figure 2. Modified small-scale photovoltaic panel

The first prototype involved the modification of an existing PV module. However, this has its disadvantages in practice. Firstly, for larger modules, one would need a thicker sheet and structural support in order to avoid bulging caused by the weight of the water. Therefore, it would be ideal if the photovoltaic module production is modified from the factory stage in order to have new modules on the market ready with a backside cooling chamber. Hence, with this aim in mind, a second prototype was designed. The second prototype differs from the first one mainly in the type of frame. The design of the second prototype involved a seamless closed cuboid serving as the frame, with the only open side being the top side in order to house the encapsulated PV cells and glass. The design for the second prototype is shown in Figure 3. The dimensions of the PV active area were 19.5cm by 10.5cm. In order to keep similar conditions between both prototypes, the water chamber was constructed with dimensions of 12.5cm by 20.5cm by 3.2cm. This resulted in a 0.82L volume of water and a 40L water volume per m^2 of active photovoltaic area. For this design, it was possible to place the contact box outside of the water chamber. This would allow for future maintenance, including the replacement of bypass diodes.

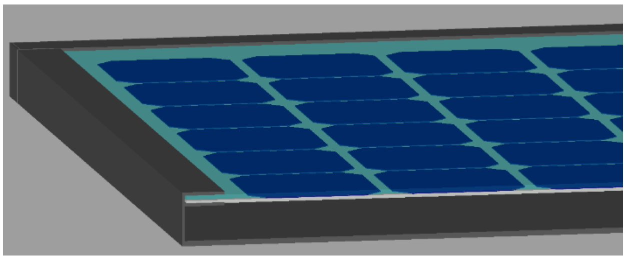


Figure 3. Cross-section of the second IPCoSy prototype

Due to the limited production capabilities, small encapsulated PV Cells with glass on top were used. However, it was noted that the back sheet of these cells was made out of an absorbing material similar to paper. Therefore, the first step was to apply three coats of acrylic sealer on the back sheet so that it would stop it from absorbing any water. Furthermore, waterproof Negative Temperature Coefficient (NTC) Thermistors were installed at the back of each PV module in order to monitor the PV cells' temperature. Hence, a 5mm Poly (methyl methacrylate) sheet was bent using an electric heater in order to create a seamless U-shape. Due to the lack of moulding capabilities, the other two sides of the cuboid had to be installed separately. Hep2O® fittings were installed on these two sides to enable the flow of water. Furthermore, in order to mimic a seamless finish, grooves were routed in the U-shape structure and filled with a sealing agent. Hence, the remaining two sides of the cuboid were tightly fit inside these grooves. Similarly, the glass, PV cells, and back sheet combination were tightly fit in other grooves routed on the top side of the frame. In a practical scenario, a moulding machine would be used in order to implement the seamless design. Another advantage of this concept is that such a prototype could be manufactured from recycled plastics. The finished second prototype can be seen in Figure 4.

Figure 4. Second IPCoSy prototype

2.2 Experimental Setup

Experiments were designed to test the prototypes mentioned above. For each experiment, two modified PVs were used together with a control PV module consisting of exactly the same material composition but without the water chamber underneath the PV cells. The idea was to monitor and compare power and temperature for a conventional module with no cooling, a new prototype with a standard backside cooling flow, and a new prototype with a modified backside cooling flow, which always leaves water stored underneath the PV module. The standard backside cooling flow involved filling the water chamber with water during cooling and allowing it to drain when cooling is switched off. This allowed us to have similar dimensions and conditions to IPCoSy while implementing a different cooling operation, similar to the backside cooling found in the literature. A 9W DC submersible water pump was used to control the flow, and a flow rate of 145L/hour was achieved.

NTC thermistors were placed in heating water together with a calibrated thermocouple in order to obtain their respective temperature-resistance characteristics. Hence, the Steinhart and Hart empirical equation, shown in Equation (1), was used to derive accurate temperatures from NTC resistance values.

$$\frac{1}{T} = A + B\ln R + C(\ln R)^3 \tag{1}$$

Where T is the temperature in Kelvin, R is the NTC resistance (in Ohms) at temperature T, and A, B, and C are empirically determined Steinhart-Hart coefficients. Figure 5 shows a block diagram of the designed experimental setup, while Figure 6 shows the design implemented in practice. The PV modules were connected to a fixed resistive load calculated using Equation (2) in order for the PVs to operate close to their maximum power point.

$$R_{LOAD} = \frac{V_{MP}}{I_{MP}} \tag{2}$$

Where R_{LOAD} is the resistive load. VMP and IMP are the PV voltage and current outputs at the maximum power point. The resistive loads were overrated in terms of power and attached to a heatsink using thermal paste in order to dissipate heat and decrease errors due to thermal drift. Furthermore, water solenoid valves and water flow meters were attached to the PV modules to control and measure water flow, respectively. A thermocouple was fitted in one of the elbow fittings in order to monitor the input water temperature. Finally, mechanical water valves were fitted in line with each PV module in order to be able to fine-tune the water flow.

A DATAQ DI-808 Data-logger was used to record data from the experimental setup, including PV Temperature, PV Power Output, Water Flow, and Water Temperature. This data-logger logged data from thermocouples at an accuracy of ± (0.1% of span + 2) while voltage data were recorded with an accuracy of ± (0.05% of span + 10 µV). Data was mostly collected at a 0.2Hz frequency, while some data sets were collected at a 5Hz frequency in order to study in detail the cooling flow. Furthermore, the data-logger was programmed in such a way as to output alarms if the module temperatures were not within the desired range. Hence, a control board was designed using an ATMEL MEGA328P microcontroller programmed with Arduino Integrated Development Environment (IDE). The control board was programmed to monitor the alarm states output by the data-logger. Hence, based on the alarm states, the control board would send a signal to a relay board in order to open or close the water solenoid valves connected to the PV modules and switch on and off the cooling pump. Figure 7 shows a flowchart of the control algorithm.

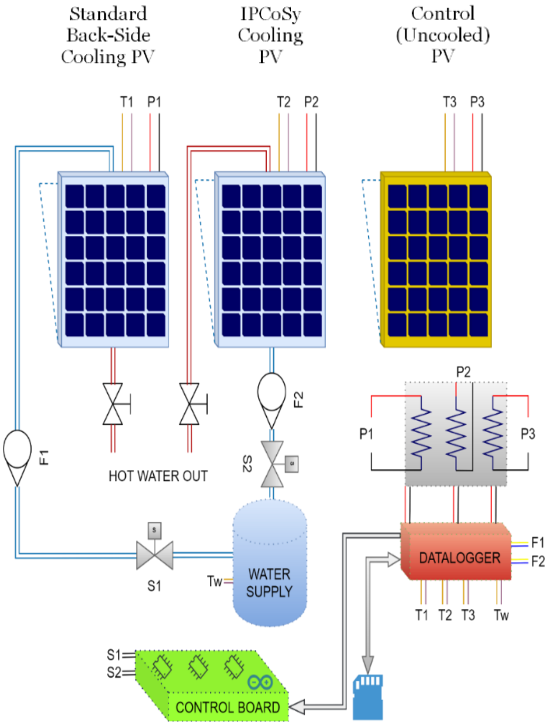


Figure 5. Block Diagram of Backside Cooling Experimental Setup. P1, P2 and P3 are the PVs DC power output. T1, T2, T3 and Tw are the PVs backside temperatures and the supply water temperature respectively. S1 and S2 are water solenoid valves. F1 and F2 are water flow sensors.

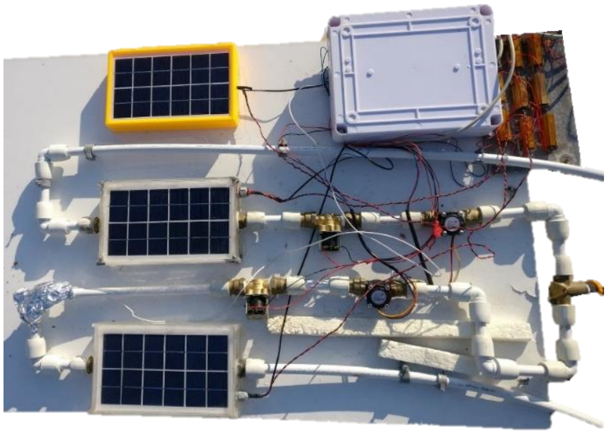


Figure 6. Experimental setup using the second IPCoSy prototype

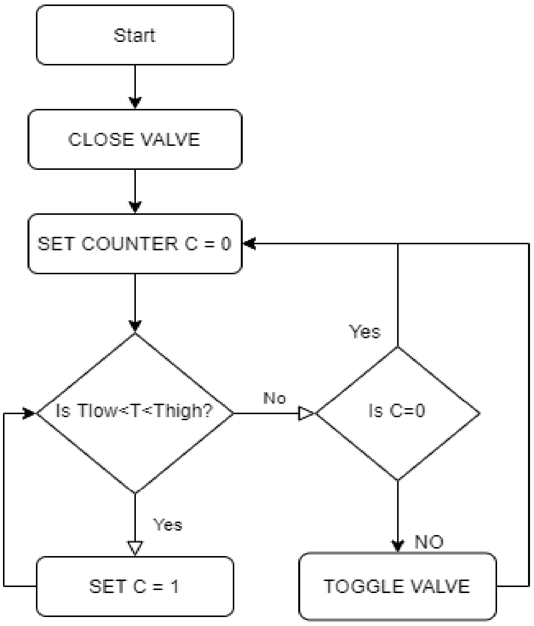


Figure 7. Flow control system flowchart

3. Results and discussion

The results obtained in this study are presented in this section. An important observation is that since small-scale panels were used for these experiments, the ratio of pump power to PV power is very high. Therefore, the net energy gain will most of the time be minimal or even negative. This will be optimized in future work when the concept will be up-scaled for full-size PVs. The percentage gross and net energy differences between the test PVs and the control (uncooled) PV were calculated using equations (3) and (4), respectively.

$$\%\ Gross\ Energy\ Difference = \left(\frac{Test\ PV_{Energy} - Control\ PV_{Energy}}{Control\ PV_{Energy}}\right) \times 100 \tag{3}$$

$$\%\ Net\ Energy\ Difference = \left(\frac{(Test\ PV_{Energy} - Pump_{Energy}) - Control\ PV_{Energy}}{Control\ PV_{Energy}}\right) \times 100 \tag{4}$$

3.1 Comparison to standard backside cooling

The IPCoSy prototype was first tested against standard backside cooling that does not retain water when the cooling is switched off. Test1 consisted of setting similar thresholds for both cooling technologies. The control system was configured to switch on the cooling flow when the PV panels reached a temperature of 45°C and switch off the flow at 35°C. Figure 8 presents the comparison between the different cooling technologies with the same control thresholds (Test1). The top graph shows the evolution of PV backside temperature during the day for the three PVs under test, while the bottom graph shows the power output of the three PVs during the day. The drop in temperature seen around 13:00 is due to the presence of clouds, as evidenced by the power curves. These results show that, although both technologies manage to keep the PV temperatures within the desired thresholds, the IPCoSy module achieved this with a much lower pump switching frequency. In this figure, both the blue and the orange curves have similar cooling rates, when the cooling flow is switched on at 45°C. However, as soon as the panels reach the 35°C threshold and the cooling is switched off, the blue curve has a much higher heating rate than the orange curve.

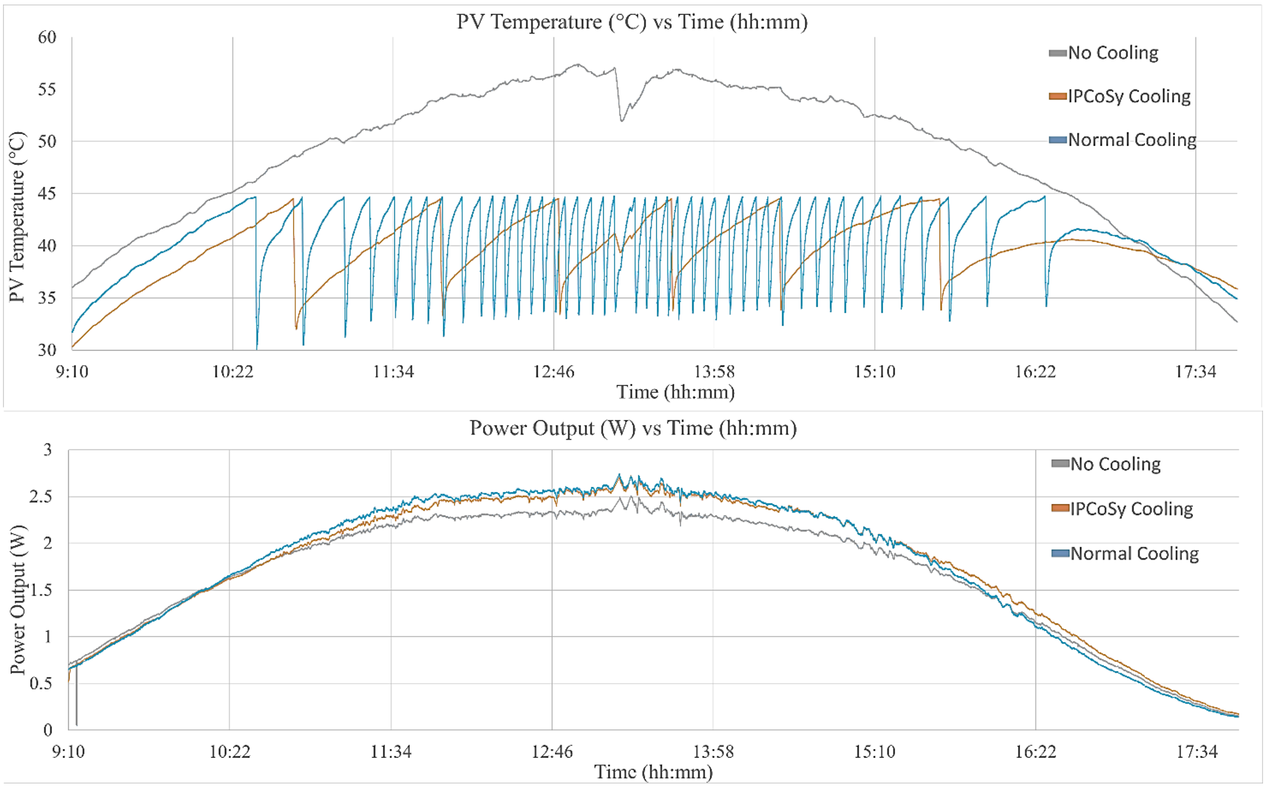


Figure 8. Comparison between different cooling technologies with same control thresholds (Test1)

This phenomenon is due to the fact that the IPCoSy panel has a volume of cool water still in contact with the backside of the PV panel even when the cooling flow is switched off. This results in a higher PV module specific heat capacity, which in turn results in a slower heating rate.

For Test 2, the PV with standard cooling was given thresholds of 35°C to 45°C while the IPCoSy PV was set between 35°C and 40°C. In this test, the IPCoSy cooling technology still achieved a higher net energy difference as shown in the results in Table 1.

Table 1. Comparison of different cooling technologies

Test 1	**Standard Backside Cooling**	**IPCoSy Cooling**	**Uncertainty**
Gross Energy Difference	5.91%	6.01%	±0.45%
Net Energy Difference	-9.13%	3.06%	
Test 2	**Standard Backside Cooling**	**IPCoSy Cooling**	
Gross Energy Difference	5.55%	7.59%	±0.45%
Net Energy Difference	-9.29%	2.42%	

3.2 IPCoSy Testing with no flow

Another set of experiments involved filling the IPCoSy prototype with water and having no extra forced flow during the rest of the day.

The hypothesis was that the added specific heat capacity would keep the IPCoSy PV cooler and therefore operate at a higher efficiency. Figure 9 shows the results from these experiments. The round and square orange markers respectively show the difference in average and maximum temperatures between the Control PV and the IPCoSy PV. The results obtained showed an increase in daily energy yield by up to 3.34% ±0.41%.

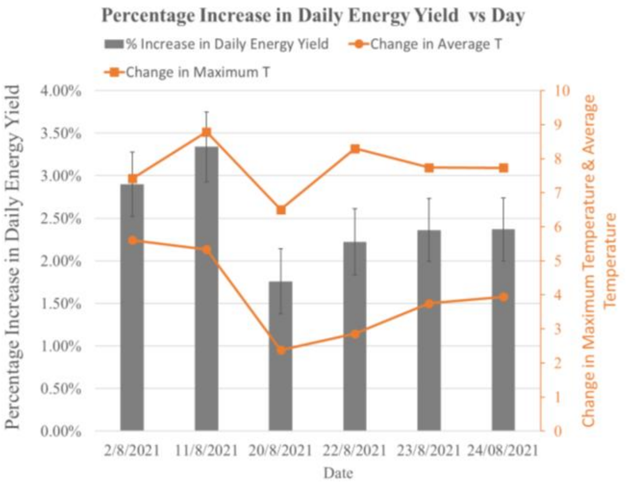


Figure 9. Results for experimentation with no flow

During the day, the panel filled with water took longer to heat up when compared to the control panel. However, during the afternoon, the control panel cooled down faster than the IPCoSy panel.

Although this resulted in the control panel working at a higher efficiency at times in the afternoon, the IPCoSy panel worked at a higher efficiency during the times of peak solar radiation. Therefore, this contributed to the overall increase in daily energy yield. This effect is shown in the sample graph in Figure 10.

3.3 IPCoSy testing with controlled flow

The final set of experiments involved setting different cooling thresholds for the IPCoSy prototype. As soon as the PV temperature reaches a certain high threshold, the cooling flow is switched on. The PV temperature will start decreasing and as soon as it reaches a certain low-temperature threshold, the cooling flow is switched off.

The aims of these experiments were to test the possible gains that can be achieved with this cooling technology and to determine ideal threshold temperatures to achieve efficient cooling. Table 2 summarises the results obtained through this set of experimentations. From the results in Table 2, it can be seen that the 35°C to 45°C range produced the highest net energy yield, in agreement with a previous study by Moharram et al. [11]. Figure 11 shows the dependency of the ratio of net energy to gross energy on the difference between the lower control temperature threshold and the water supply temperature and the difference between the upper control temperature threshold and the maximum temperature reached by the control panel.

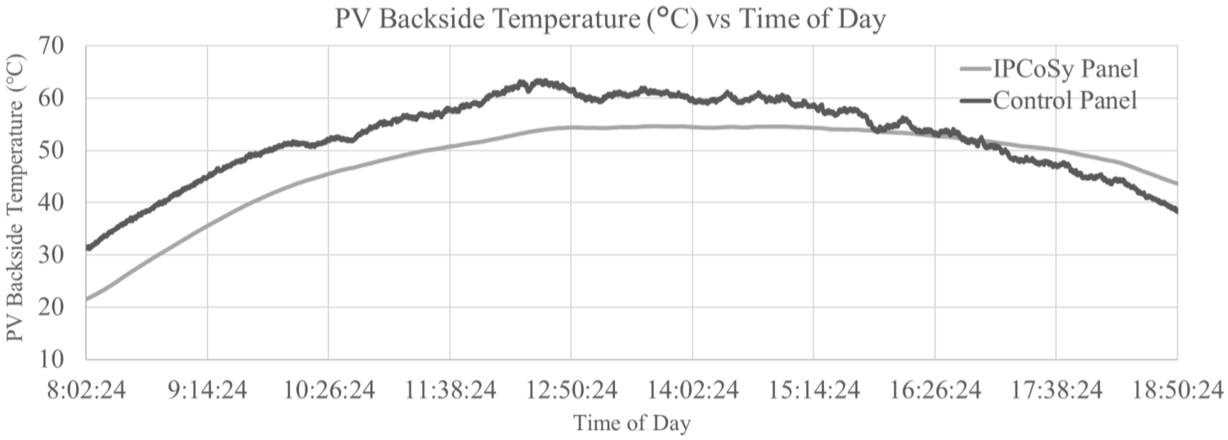


Figure 10. Sample graph of experimentation with no flow

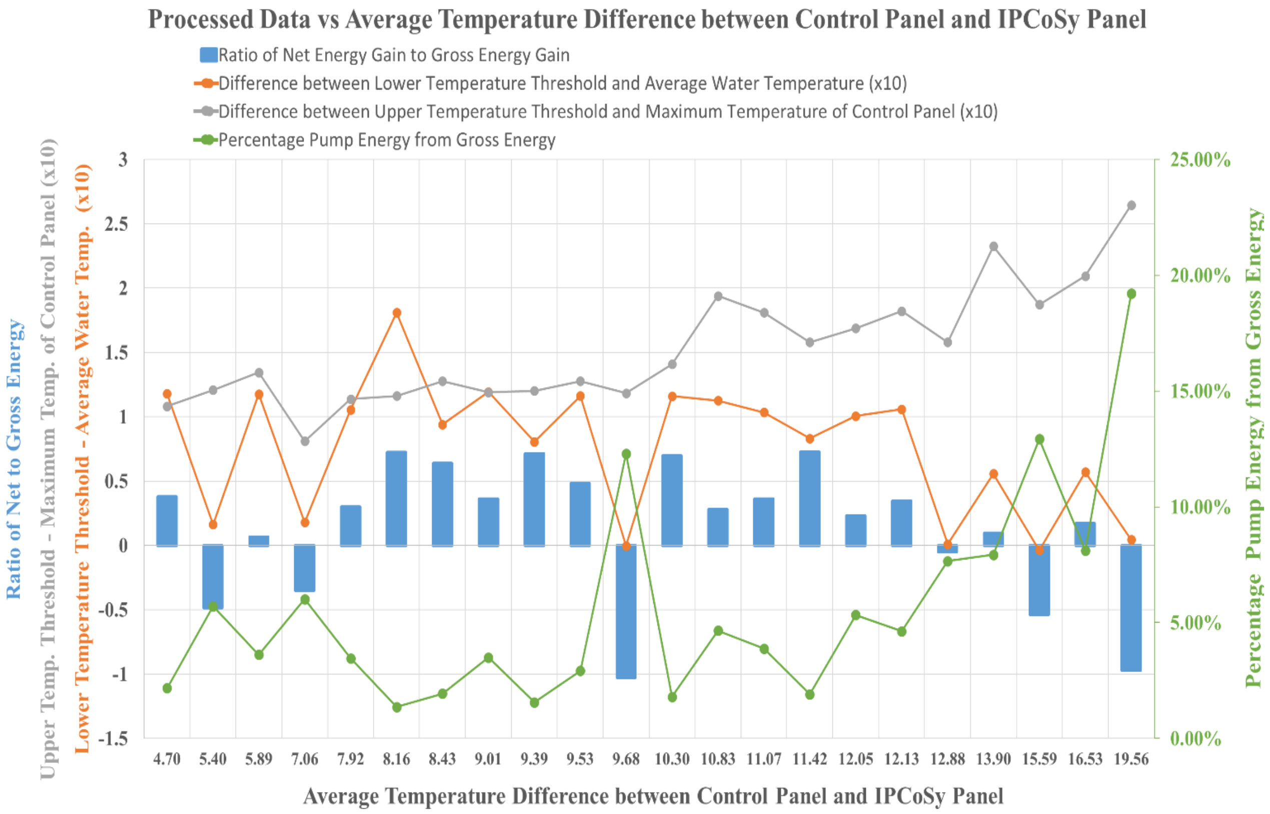


Figure 11. Forced flow experiments data analysis

The data shows that when lower control temperature thresholds are set close to the water supply temperature, the pump consumption increases since the cooling flow has to be on for a longer time in order to reach the desired threshold. Furthermore, setting a maximum temperature that is much lower than the control panel's maximum temperature will result in the pump switching on at a higher frequency and therefore wasting more power. These results show that, for the best case scenarios, the difference between the upper control temperature and the maximum temperature of a non-cooled PV should be in the range of 12°C to 16°C while the difference between the lower control temperature threshold and the water temperature should not be less than 8°C.

4. IPCoSy benefits and future work

Throughout this study, it was observed that the gains that can be achieved with the IPCoSy prototype are considerable. However, these gains can be limited by various factors, including the heating up of the water source and the pump energy consumption. Therefore, in order to maximize gains even above those reported in this study, one should install the IPCoSy panels in ideal scenarios where the water resource volume is large and in places where a water flow is already present. If the IPCoSy panel is used in floating installations, available water can be used as the cooling fluid. This would mean that hot water can be discarded without heating the water source or wasting any water. Another ideal application for the IPCoSy panel is in powering reverse osmosis plants. The IPCoSy panel would act as the water transfer medium instead of conventional water pipes. Therefore, the flow generated by the reverse osmosis would keep the IPCoSy panel operating at ideal low temperatures, resulting in an optimized electrical efficiency. In return, the energy produced by the PVs would be used to power the reverse osmosis plant.

Moreover, the IPCoSy panel can also be installed in places that require water heating, such as at the residential level or even in industrial scenarios with large boilers. In such an installation, the IPCoSy panel would provide pre-heated water for the boiler while also using the water flow to keep the solar panel at a lower temperature. Since water exiting from the IPCoSy panel will be at a higher temperature than the water source, this would greatly increase the efficiency of the building's water heating system. Besides the energy gains, the IPCoSy panel provides other benefits, such as the weight of the water acting as a ballast to increase installation stability and, in very hot climates, the lower maximum PV temperature will result in a longer PV lifetime. The design in itself only involves a small modification to the current fabrication process of PV panels. Therefore, the capital cost will be mostly limited to the added material for the back-plate. Furthermore, IPCoSy does not involve any complex setting up by the user, similar to what is required for spray cooling, since the PV panel already incorporates the cooling chamber and only some basic plumbing is required to set it up.

The net energy gains need to be further optimized in future work when the prototypes are scaled up to full-size panels. This will occur naturally since in this study, small, low-power PV panels were used. In contrast, pumps with lower power than 9W could not be used since these wouldn't be able to overcome the required head. Therefore, this resulted in a high ratio of pump power to PV power. However, in large-scale prototypes, a lower ratio will be possible.

Table 2. Results of testing with controlled flow

Temperature thresholds: 35°C to 45°C, flow rate: 145L/hour			
Date	**Net energy difference from control**	**Gross energy difference from control**	**Uncertainty**
03/08/2021	3.75%	5.18%	0.38%
05/08/2021	4.36%	6.27%	0.38%
06/08/2021	3.59%	5.63%	0.38%
07/08/2021	5.42%	7.47%	0.38%
08/08/2021	4.11%	5.77%	0.39%
Temperature thresholds: 25°C to 37°C, flow rate: 145L/hour			
09/08/2021	-4.92%	9.2%	0.39%
10/08/2021	-10.49%	10.81%	0.40%
Temperature thresholds: 25°C to 45°C, flow rate: 145L/hour			
12/08/2021	-1.94%	4.00%	0.40%
13/08/2021	-1.63%	4.66%	0.38%
15/08/2021	-0.39%	7.87%	0.39%
16/08/2021	-6.63%	6.47%	0.38%
Temperature thresholds: 35°C to 37°C, flow rate: 145L/hour			
17/08/2021	1.7%	7.43%	0.39%
18/08/2021	2.6%	7.57%	0.39%
Temperature thresholds: 30°C to 35°C, flow rate: 145L/hour			
28/08/2021	1.83%	10.82%	0.38%
29/08/2021	0.9%	9.60%	0.42%
Temperature thresholds: 30°C to 40°C, flow rate: 145L/hour			
30/08/2021	2.08%	5.77%	0.39%
31/08/2021	2.35%	6.48%	0.40%
01/09/2021	0.27%	4.03%	0.45%
02/09/2021	2.89%	5.99%	0.38%
05/09/2021	1.92%	6.89%	0.41%
06/09/2021	1.37%	3.63%	0.39%
Temperature thresholds: 30°C to 37°C, flow rate: 145L/hour			
17/09/2021	1.56%	5.20%	0.39%

For example, taking the results of 07/08/2021 from Table 2:

- During the day, the 9W pump had to work for a total of 240s with a flow rate of 145L/hour.
  - At this flow rate, the 1.54L volume of water inside the water chamber is completely exchanged with cooler water after about 38s. Although this calculation assumes that the hot water is pushed out with negligible mixing, it is also in close agreement with actual data.
- Considering a 350W full-scale solar panel [12], the water chamber would have approximate dimensions of 1.944m x 0.976m x 0.035m and a volume of 66.4L.
  - In a Mediterranean environment, such a panel would produce approximately 581kWh/year or 1.59kWh/day.
  - This means that after a 7.47% gain, as reported in Table II, the PV panel would produce 1.71kWh/day.
- Considering a 20W pump with a flow rate of 1,100 L/hour.
  - At this flow rate, the 66.4L volume of water inside the water chamber is completely exchanged with cooler water after about 217s. This calculation assumes that the hot water is pushed out with negligible mixing.
  - This means that this full-scale setup will have the pumps running approximately 5.7 times longer than the small-scale setup (1368s). This would result in a daily pump energy consumption of 7.6x10-3 kWh.
- Therefore, using equation (2), the percentage of net energy gain would be 7.07%, which is higher than the 5.42% reported in Table 2.

These assumptions and results will be verified in future work, which is already underway. Furthermore, the design needs to be improved when scaling up since structural integrity will start playing a major role.

5. Conclusion

This article presents the results arising from the testing of a new type of photovoltaic panel that incorporates an innovative backside cooling technique. This photovoltaic module, termed IPCoSy, can achieve energy gains of up to 10% when using a controlled forced flow and up to 3% when using no flow. The main advantage of IPCoSy cooling system is that when the cooling flow is switched off, a volume of water remains in contact with the backside of the PV module resulting in an added specific heat capacity. Therefore, the temperature of the PV will take longer to increase thus, reducing the pump switching frequency. Furthermore, when installed in ideal scenarios, such as in reverse osmosis plants or in places using water heaters, the total efficiency gain will be higher than what is reported in this paper.

Nomenclature

PV: Photovoltaic
PCM: Phase Change Materials
SRH: Shockley-Read-Hall
NTC: Negative Temperature Coefficient
kWh: Kilowatt-hour
K: Kelvin
^{o}C: Degree Celsius
IDE: Arduino Integrated Development Environment

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Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically concerning authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere in any language.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request. Data is not publicly available since it will be used for the submission of a Ph.D. thesis.

Conflict of interest

The authors declare no potential conflict of interest.

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