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*Original Article*

# Comparative Analysis and Performance of Solar PV Panel with V-Trough and Front Surface Water Cooling versus without V-Trough and without cooling for Powering RO Desalination Unit

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***Abstract*** *- Water scarcity is one of the world's problems belongs to high population, climate changes, water pollution, and groundwater extraction. Solar PV-based RO systems provide a sustainable solution to compensate this challenge, especially in high solar energy sources-oriented regions. In this study, a V-Trough PV with front surface water cooling is proposed to increase the performance of the PV system used for the 50 LPH RO unit. Both standalone PV and V-Trough PV with front surface water cooling were experimentally compared under atmospheric conditions. The aim of this exercise was to improve the power produced, whilst at the same time, attempt to bring PV operating temperature into the realms of standard test conditions to help with efficiency losses. The results show that front surface water cooling reduced the operating temperature of the PV panel, enhancing a temperature reduction of 29.2°C and a mean reduction of 24.6°C as compared to the reference panel. The V-through PV system showed significant electrical performance. The V-Trough PV with Cooling enhances the power output on average by 35.3%, with a 61.7% maximum increase during peak time. Statistical analysis showed the reliability and consistency of the results. The results showed that the V-Trough concentration with front surface water cooling for PV would be beneficial for improvement in performance under the hot climate conditions, especially where water purification is required.*

***Keywords*** *- Renewable Energy, Desalination, V-Trough, Front Cooling, PV-RO.*

## 1. Introduction

Water crises are a critical global issue facing due to high population, climate change, uneven use of water, and underground water depletion. Presently, available sources of fresh water are becoming scarcity at many parts of the world, specifically in arid and semi-arid regions. Renewable energy-based water treatment technology should be compensated these issues. RO system is frequently used due to its low power consumption and producing desired drinking water. Nevertheless, conventional RO has operated using electricity, which is mainly produced from fossil fuels, which can increase the operational cost and also result in high air pollution in the environment. Therefore, a solar-PV powered RO system is a sustainable, cost-effective, and energy-saving substitute as there is lesser reliance on the fossil fuel-driven grid power.[1]. Almetwally et al. [2] discussed a systematic review on solar-powered reverse osmosis desalination technologies, and a detailed analysis on integration strategy (PV, CSP, Hybrid) are described. The results show that PV-driven RO systems are one of the key sustainable water sources in the future, and issues like the solar energy intermitted and the optimization were required more research. Raninga et al. [3] studied a solar thermal energy-assisted cascade Rankine cycle coupled with reverse osmosis desalination and conducted the analysis for energy, exergy, and economy. It indicates that renewable energy could contribute to an efficiency and sustainable RO system.

The performance of the solar PV system can be adversely affected by solar radiation and surface temperature. In hot climates, high cell temperature can lead to decreased output voltage and electrical efficiency so that PV power generation decreases [4, 5]. Ravi Shankar Yadav et al. [6] show that changes in solar irradiance and atmospheric temperature have a great influence on PV performance. They confirm that the PV efficiency decreases with an increase in cell temperature. Based on their findings, the review by Raad et al. [7] on PV thermal management found that PV efficiency decreases by 0.45 to 0.6 percent every 1°C rise in working temperature; effective water cooling schemes could significantly reduce the module temperature and improve its electrical performance. In view of this underperformance of solar PV, there are various strategies to improve PV efficiency, which have been prioritized by researchers. One of the methods is the modification of solar cell materials through novel semiconductor techniques and advanced cell structures so that the cell can absorb more light and less energy is wasted. While this can improve the conversion efficiency of the cell, its manufacturing process is usually complicated and costly. Another approach has been actively investigated, which is based on thermal control by cooling methods. Several research on passive and active cooling methods have been carried out in order to reduce PV operational temperature and consequently improve electrical efficiency.

Bukar et al. [8] provide a thorough review of active and passive cooling technologies applicable to photovoltaic devices and the overall assessment of each cooling technology on reduction in module temperature as well as enhancement in electrical efficiency. Their work concludes that air cooling, water cooling, heat pipe, and liquid immersion cooling are successful thermal control methods, and the choice depends on climate, implementation cost, and system configuration. They also point out that water-based Cooling is a suitable thermal cooling technique, especially for CPV, due to its simplicity. Utomo et al. [9] performed a detailed review on Cooling and power enhancement systems of PV systems based on classifying the methods of cooling into three forms: conduction cooling, convection cooling, and radiation cooling. According to the study, cooling with nanofluid offers high temperature reduction, while phase change material, together with thermoelectric generators, shows a large enhancement in energy generation. The paper summarized the technological and economic challenges faced in the field of advanced cooling technologies and it emphasized the fact that effective and economical PV thermal management methods need to be investigated.

Badgujar et al. [10] experimentally investigated phase change material based cooling and reported effective temperature reduction and enhanced electrical performance under high solar irradiance. Installation cost becomes higher for the PCM based system; however, the selected material needs to ensure long-term operation. Apart from the cooling system, the orientation and inclination of the PV module relative to solar irradiance has an effect on the PV module electricity generation. Correct orientation of the PV panels increases the amount of incident irradiance and the amount of energy that is generated during the course of the day.

Togun et al. [11] recently performed a survey regarding PV/T developments and introduced several types of hybrid cooling systems, such as nanoparticles, PCMs, fins, and heat pipes for better thermal control and energy saving. It was also concluded that the hybrid cooling systems perform better than the separate ones; they add complexity and cost to the systems, and so an efficient, low-cost, and easy system should be developed.

Surface cooling using water is one of the simplest and most practical techniques. It is economic and easy to implement as compared to PCM or nano fluid cooling. Experiments observed that water on the PV surface can increase the power output and efficiency.

Shalaby et al. [12] carried out an experimental study on back-surface water cooling of PV modules, reporting that a simple and low-cost cooling system increased power generation by approximately 14.1% and improved panel efficiency from 17.4% to 19.8% compared with an uncooled PV module. A similar work conducted by Dorobanțu et al. [13] has stated that water is used to cool the front surface of the module not only to decrease the module temperature, but also to decrease optical reflection losses and to produce self-cleaning, thus improving electrical characteristics and ensuring long-term operation of the PV system.

Along with thermal management, optical concentration is also an efficient method that shows high performance of the PV system. A low-concentration photovoltaic system can be used to focus more solar irradiation on the surface of the PV cell, resulting in more electrical power. The V-trough concentrator has been pursued by many researchers because of its simple structure, low fabrication cost, and its capability to concentrate solar energy without an active sun-tracking system. There are lots of experimental investigations reporting the benefit of using a V-trough concentrator to concentrate solar energy without the requirement for a costly tracking device and complex optical systems [14].

Various studies on concentrator PV systems confirm the potential application. Baig et al. [15] investigated building-integrated concentrating photovoltaic systems and reported that concentrator designs can reduce the required PV area while improving overall energy generation compared with conventional flat PV modules. Similarly, Ağbulut et al. [16] worked on low-concentration V-trough systems, which have demonstrated that multiple reflections on the reflector surfaces enhance the incident solar irradiance on the PV module, leading to greater electrical power. Various experiments indicated that optimization of the V-trough shape could increase power generation by 16% without using a solar tracking system. Additionally, Shohani et al. [17] carried out simulation and ray-tracing studies, demonstrating that reflector angle, vertex angle, and reflector material significantly influence optical concentration performance and overall system efficiency. Elminshawy et al. [18] carried out the experimental optimization studies, which have also confirmed that proper geometric design of V-trough concentrators can further improve photovoltaic system performance. Ghasemian et al. [19] experimentally and numerically investigated a low-concentration PV/T system integrated with V-trough reflectors and cooling tubes equipped with twisted tapes. The work showed the concentration ratio of 2, and with an improved cooling configuration, the electrical power had increased from 59.2 W to 67.5 W, which shows the efficient Cooling in sustainable concentrated PV systems.

Although optical concentration increases the amount of solar energy reaching the PV surface, it also increases the operating temperature of the solar cells. Such extra thermal load could reduce the efficiency and might lead to a decrease in solar potential unless it is cooled down properly. Hence, the thermal management requirement becomes mandatory for CPV systems, and a number of advanced cooling strategies are explored for these purposes. Besides conventional cooling strategies like water cooling, many others like microchannel cooling, water spray cooling, Phase Change Materials (PCM), and hybrid cooling approaches have been explored recently. A detailed review of thermal control techniques for PV-T systems has been presented by Bian et al. [20] that includes air cooling, water cooling, nanofluid Cooling, PCM cooling, heat pipe cooling, and refrigerant Cooling. The author observed that the water cooling has high efficiency of heat removal at comparatively low system complexity, but high-complexity techniques, such as the hybrid cooling method, enhance performance, but cost and design complexity of the system. Tahir et al. [21] performed a review on PVT management and reported that active cooling systems, including water spray and microchannel cooling, can drastically decrease the temperature and enhance electrical performance. However, such techniques are more complex, high-energy consumption, and operational costs. These approaches might be useful while designing a real system.

The available literature clearly demonstrates that both water cooling and V-trough concentrators can individually improve photovoltaic performance. Very few studies have explored their combined use experimentally, especially for photovoltaic-powered reverse osmosis desalination systems operating in a real environment. Most existing research focuses on either thermal management or optical concentration independently, while the combined influence of front-surface water cooling and V-trough concentration on both thermal and electrical performance remains insufficiently explored. In addition, experimental investigations on the application of this integrated approach for PV-powered RO desalination systems are scarce.

Based on this identified research gap, the present study investigates the integration of a V-trough concentrator with front-surface water cooling on a photovoltaic module powering a reverse osmosis desalination unit. The innovation presented in this work is the fusion of optical concentration and thermal management within the same experimental apparatus and assessment of their cumulative effect under outdoor working conditions. The purpose of this study is to determine the performance improvement of PV powered RO desalination system by this integrated method, and also make a simple technique suitable for practical and reliable applications.

## 2. Experimental Setup and Methodology

The experimental study was carried out to evaluate the performance of a conventional PV panel and a V-Through concentrator PV panel with front surface water cooling for the application of RO desalination. A schematic of the PV-RO experimental setup is shown in Figure 1.

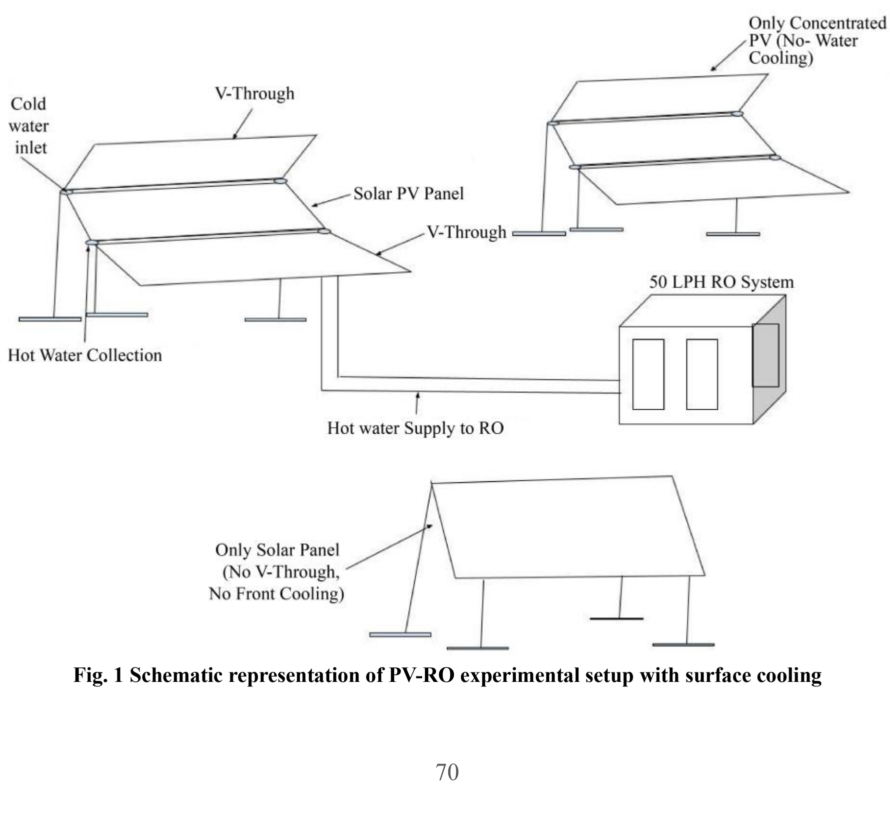


**Fig. 1 Schematic representation of PV-RO experimental setup with surface cooling**

### *2.1. Description of the PV System Configuration*

The setup consists of two solar PVs. One has an experimental panel with a V-Through reflector and a front surface water cooling, as illustrated in Figure 2. Second has a standalone PV panel, which is the reference panel. Both were installed in the same plane, which have similar ambient temperature and wind conditions throughout the experiment. Both panels were commercial TEL24P320 polycrystalline silicon PV modules manufactured by TopSUN Energy with a rated power output of 320 W under Standard Test Conditions. Each PV module had a gross surface area of 1.77 m² with dimensions of 1.9 m × 0.9 m. At STC of this PV panel were the short circuit current by 9.2 A; open circuit voltage by 45.28 V; maximum power current by 8.6 A; maximum power voltage by 37.2 V; and fill factor by 0.77. PV modules were installed with a fixed tilt angle corresponding to the latitude of Gandhinagar, Gujarat, India, in order to extract maximum solar energy during the entire experiment.

**Fig. 2 The experimental set-up on the terrace of LDRP Institute of Technology, Gandhinagar**

### *2.2. Instrumentation and Measurement Devices*

Various instruments were mounted on the system in order to get all the electrical, thermal, and environmental performance unit measurements. A solar meter was fixed on the system in order to obtain the solar irradiance values. A digital multimeter is used to measure the voltage and current. A thermocouple, thermometer, and data logger were used to measure the PV surface temperature. Water flow rate was observed using a beaker and a stopwatch. The range, accuracy, and uncertainty of the instruments were illustrated in Table 1.

**Table 1. Accuracy of the instruments used in the experiment**

| Instrument | Range | Accuracy | Uncertainty |
|---|---|---|---|
| Digital Solar Power Meter | 1999 W/m$^2$ | ±10 W/m$^2$ | 5.77 W/m$^2$ |
| Mastech Digital Multimeter | Voltage: 400 mV to 600 V<br>Current: 400μA to 10 A | Voltage: ±0.5 %<br>Current: ±2.0% | Voltage: 0.288 V<br>Current: 1.15 A |
| Flus IR-865 Infrared Thermometer | -50 to 1850 °C | ±2% or ±2 °C | 1.15 °C |
| Flowrate measuring beaker | 0-1000 ml | 10 ml | 5.77 ml |
| Stopwatch | 0-99 hrs | 0.01 s | 0.005 s |

### *2.3. Front Surface Water Cooling Arrangement*

The front surface water cooling system was developed for equally distribution of water over the PV surface to remove the heat during sunshine. A PVC pipe of 1 inch diameter and 2m length was mounted on the panel with 40 numbers of 1.5 mm diameter holes equally distributed in a straight line over the PV surface. Specifically, three holes are provided per PV cell column to reduce the local thermal load and ensure cooling performance.

A 500-liter water tank was set up and connected to cool the panel. Water was allowed to flow using a control valve, and a 2 m long pipe carries the water from the tank to the panel surface. Water flow was run continuously for each experiment at the rate of 90 LPH. A large-diameter PVC pipe was used at the bottom of the PV panel to collect runoff water for further reuse. The water was stored in a collecting tank it was recirculated back to the storage tank using a low-head centrifugal pump.

The energy consumption related to the water circulation was very low due to operating under a small pressure head. The system mainly depends on gravity-assisted flow at small pipe lengths, which reduces the pumping energy and can be negligible from the total power generated by the PV. However, the net electrical output produced through temperature reduction was more than the energy consumption takes by the cooling system. This makes a viable cooling arrangement for practical operations.

### *2.4. V-Through Concentrator Arrangement*

The V-Through geometry and the rate of flow of cooling water are essential parameters in the design for the highest optical concentration and the highest thermal load of the PVs. Figure 3 shows the configuration of geometric and tilted angles of the V-Through reflectors. The V-Through at an inclination angle of 9° at lower side and 57° at the higher end was adopted to utilize majorly of solar radiation, which is based on basic optics principles previously reported in analytical and experimental literature [7, 10]. The combined use of a tilt angle (9°) and a was chosen, to give a wide range, and collect radiation during the day without active tracking of the sun. The lower angle allows for morning radiations, and the higher angle allows for afternoon radiations. This dual-angle configuration provides daily energy improvements and while maintains balanced structural with passive operation. The concentrator was under stationary position over the experimental period.

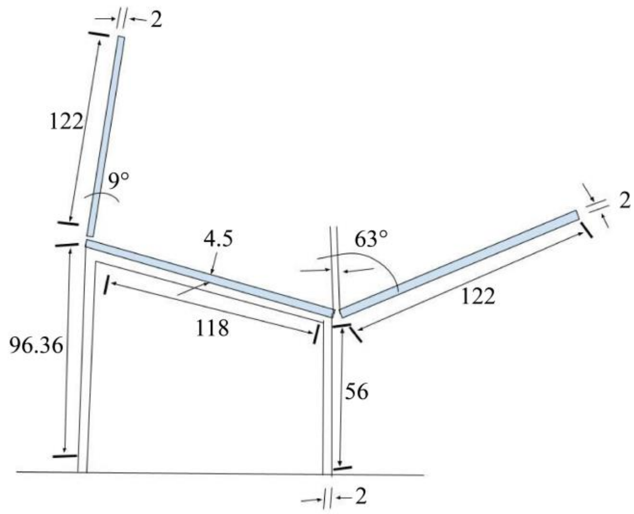


**Fig. 3 Angle of the V-Through during the experimentation**

### *2.5. Temperature Measurement and Sensor Placement*

The thermal behaviour of both PVs was accurately monitored using the temperature sensors, which were installed in a 16-channel data acquisition system. Thermocouple sensors were placed (as shown in Figure 4) at five locations on the front and five locations on the bottom of the PV panel to capture behaviour of temperature variations. This technique was also used to measure the mean surface temperature distribution over the PV module.

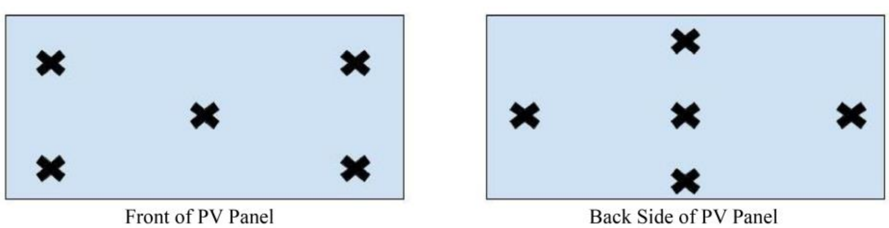


**Fig. 4 Position of the thermocouple sensors for the surface temperature measurement of the PV panel**

### *2.6. Experimental Duration and Data Collection*

All experimental runs have been performed on the day between March 25 to March 31, 2023, under the clear sky conditions. Readings of were taken at an interval of 30 minutes from 09:30 to 16:30 local time. During each interval, solar irradiance, voltage, and current, surface temperatures, and water flow rates were noted for both panels to perform the comparative analysis.

### *2.7. Performance Assessment*

*2.7.1. Energy and Electrical Performance Analysis*

The electrical performance analysis can be carried out by using the measured solar irradiation, power output, and efficiency. Instantaneous voltage and current values of the PV were used for estimating the electrical power of the PV:

$$P = V.I \quad (1)$$

Where P is the electric power in W, V and I are the voltage in V, and current in A, respectively. The solar input can be determined based on:

$$P_{in} = G.A \quad (2)$$

Where $P_{in}$ is the solar power in W, G is the measured total solar irradiance in W/m², and A is the PV panel area in m². The electrical efficiency of the PV panel was calculated as:

$$\eta = \frac{P}{P_{in}}.100 \quad (3)$$

Where $\eta$ is the PV efficiency (%). With these parameters, a calculation was carried out comparison for both standalone and V-Through PV panels with front water cooling under operating conditions.

*2.7.2. Statistical Analysis of Experimental Data*

The power output and efficiency data were examined using statistical analysis to evaluate their consistency. The standard Deviation (σ) was determined using:

$$\sigma = \sqrt{\frac{1}{n-1}.\sum_{i-1}^{n}(x_i - \mu)^2} \quad (4)$$

Where, $x_i$ is the experiment parameter value (i.e., power output or efficiency), and $\mu$ is the mean value of all experimented parameters. The Coefficient of Variation (CV) was determined based on:

$$CV = \frac{\sigma}{\mu}.100 \quad (5)$$

A lower CV indicates the variability consistency in performance. Statistical parameters were used to compare the standalone PV and the V-Through PV over the experimental data.

*2.7.3. Uncertainty Analysis*

Uncertainty analysis was carried out to determine the confidence level of experiments and to improve the performance under measuring errors. The uncertainty of power output was calculated using the standard error method, where a lower value showed more convincing measurements. The relative uncertainty of the standalone PV and the V-trough PV system was calculated as follows:

$$\left(\frac{\Delta P}{P}\right) = \sqrt{\left(\frac{\Delta V}{V}\right)^2 + \left(\frac{\Delta I}{I}\right)^2} \quad (6)$$

Where $\Delta P$, $\Delta V$, and $\Delta I$ are the absolute values of uncertainties of power, voltage, and current, respectively.

## 3. Results and Discussion

The performance of the V-Through concentrator-based solar PV with a front surface water cooling was experimented and compared with a standalone PV. The standalone PV system without a reflector and Cooling was used as the baseline for performance comparison. Both PVs were installed in the same plane to get consistent solar irradiance and ambient environmental conditions. The thermal and electrical performance and efficiency improvement achieved due to the combined effect of V-Through concentration and front surface cooling is described in the following subsections.

### *3.1. Thermal Performance and Temperature Reduction Analysis*

In this study, front surface cooling water was distributed uniformly across the PV surface via six nozzles at a 90 LPH rate of flow. The temperature at the back and front surfaces of PV panels was recorded at the location shown in Figure 4.

**Table 2. Reduction in PV panel temperature due to the front water-cooling technique**

| Sr. No. | Time | Surface Temperature (ºC) | |
|---|---|---|---|
| | | Standalone PV (Reference Panel) | V- Through PV with Front Cooling |
| 1 | 09:30 | 48.1 | 25.4 |
| 2 | 10:00 | 48.1 | 25.6 |
| 3 | 10:30 | 48.0 | 25.7 |
| 4 | 11:00 | 46.2 | 25.5 |
| 5 | 11:30 | 51.7 | 31.1 |
| 6 | 12:00 | 55.9 | 33.0 |
| 7 | 12:30 | 61.0 | 33.1 |
| 8 | 01:00 | 57.0 | 32.3 |
| 9 | 01:30 | 55.7 | 32.0 |
| 10 | 02:00 | 55.9 | 33.4 |
| 11 | 02:30 | 60.1 | 32.4 |
| 12 | 03:00 | 59.8 | 30.7 |
| 13 | 03:30 | 59.4 | 30.2 |
| 14 | 04:00 | 55.3 | 28.1 |
| 15 | 04:30 | 53.9 | 28.3 |

Table 2 shows the variation of surface temperature transient on standalone PV and V-Through PV with front surface cooling. As observed, the reference panel experienced a steady increase in surface temperature with an increase in solar irradiance, with a maximum temperature rise of 61°C on midday. On the other side, the PV panel with front surface water cooling showed lower temperatures throughout the experiment. High cooling performance was observed under the high solar flux conditions during 11:30 and 14:30, where the temperature difference between the two PV panels was also found to be high. The high temperature decreased by 29.2°C during 12:30 and mean reduction by 24.6°C. The remarkable temperature drop indicates that the front surface cooling significantly decreases surface temperature by accumulating the heat both from high solar intensity and from the V-Through concentrator as a heat input. A lower and stable operating temperature is the key to PV modules, as the temperature of the surface increases leads to a drop in open circuit voltage and electric power of the module. Stabilized operating temperature in case of cooled PV module offers an excellent basis for high electric performance, which is detailed in the below sub-section.

### 3.2. Electrical Power Output Performance

PV Panel Input Power, Output Power, and Conversion efficiency were estimated by these values with the solar irradiance, as shown in Table 3.

**Table 3. Comparison of power output and efficiency of experimented solar PV panels**

| Time | Total Radiation ($W/m^2$) | Power Input (W) | Standalone PV (Reference Panel) | | V- Through PV with Front Cooling | |
|---|---|---|---|---|---|---|
| | | | Power Output (W) | Efficiency (%) | Power Output (W) | Efficiency (%) |
| 09:30 | 490 | 867.3 | 163.4 | 14.5 | 223.1 | 19.8 |
| 10:00 | 510 | 902.7 | 214.8 | 18.3 | 238.4 | 20.3 |
| 10:30 | 620 | 1097.4 | 262.4 | 18.4 | 265.4 | 18.6 |
| 11:00 | 775 | 1371.7 | 261.1 | 14.7 | 293.3 | 16.5 |
| 11:30 | 943 | 1669.1 | 244.3 | 11.3 | 333.7 | 15.4 |
| 12:00 | 882 | 1561.1 | 227.4 | 11.2 | 353.5 | 17.4 |
| 12:30 | 1080 | 1911.6 | 297.9 | 12.0 | 323.9 | 13.0 |
| 13:00 | 972 | 1720.4 | 306.1 | 13.7 | 392.9 | 17.6 |
| 13:30 | 893 | 1580.6 | 282.5 | 13.8 | 417.1 | 20.3 |
| 14:00 | 726 | 1285.0 | 267.9 | 16.0 | 348.2 | 20.9 |
| 14:30 | 827 | 1463.8 | 267.6 | 14.1 | 335.5 | 17.6 |
| 15:00 | 890 | 1575.3 | 195.6 | 9.6 | 293.3 | 14.3 |
| 15:30 | 726 | 1285.0 | 216.7 | 13.0 | 361.7 | 21.7 |
| 16:00 | 690 | 1221.3 | 200.9 | 12.7 | 347.8 | 21.9 |
| 16:30 | 550 | 973.5 | 184.0 | 14.5 | 331.8 | 26.2 |

It can be observed that the V-Through PV with front Cooling constantly provides higher power output compared to the reference panel during the whole day.

In the morning hours, there was lowest increment was observed in power output due to lower ambient temperatures as well as solar irradiance. However, after some days, solar irradiance increased, which leading in performance gap between the two panels to be wider.

The major improvement in power output was observed in the afternoon, when the reference panel on its elevated temperatures. At 13:30, for example, the reference panel produced 282.5 W, whereas the V-Through PV cooled panel produced 417.1 W under the same conditions, which showed a maximum power enhancement of 61.71%.

Over the entire experiments, the increase in average power output achieved by V-Through with front cooling configuration was observed to be 35.26%.

The drastic improvement during peak temperature periods showed the significant effect of the V-Trough concentrator and front surface cooling. While the V-Trough releases additional heat when increases the incident solar radiation. This enhances the temperature and allows PV to operate at nearly standard test conditions.

### 3.3. Efficiency Enhancement and Performance Trends

The electrical efficiency of these PV systems was calculated, which is a ratio between electric power output and the solar radiation as an input. As predicted, the efficiency of the reference panel showed a decrement during midday due to high cell temperature. Additionally, the V-Trough PV with Cooling has higher efficiency over the day. Table 3 shows performance indices where the maximum efficiency of the V-Trough PV is found to be 26.2% during the afternoon, compared to 14.5% for the reference panel. Even at high irradiance periods, when thermal losses are relatively high, the cooled panel constantly showed lower performance of standalone PV.

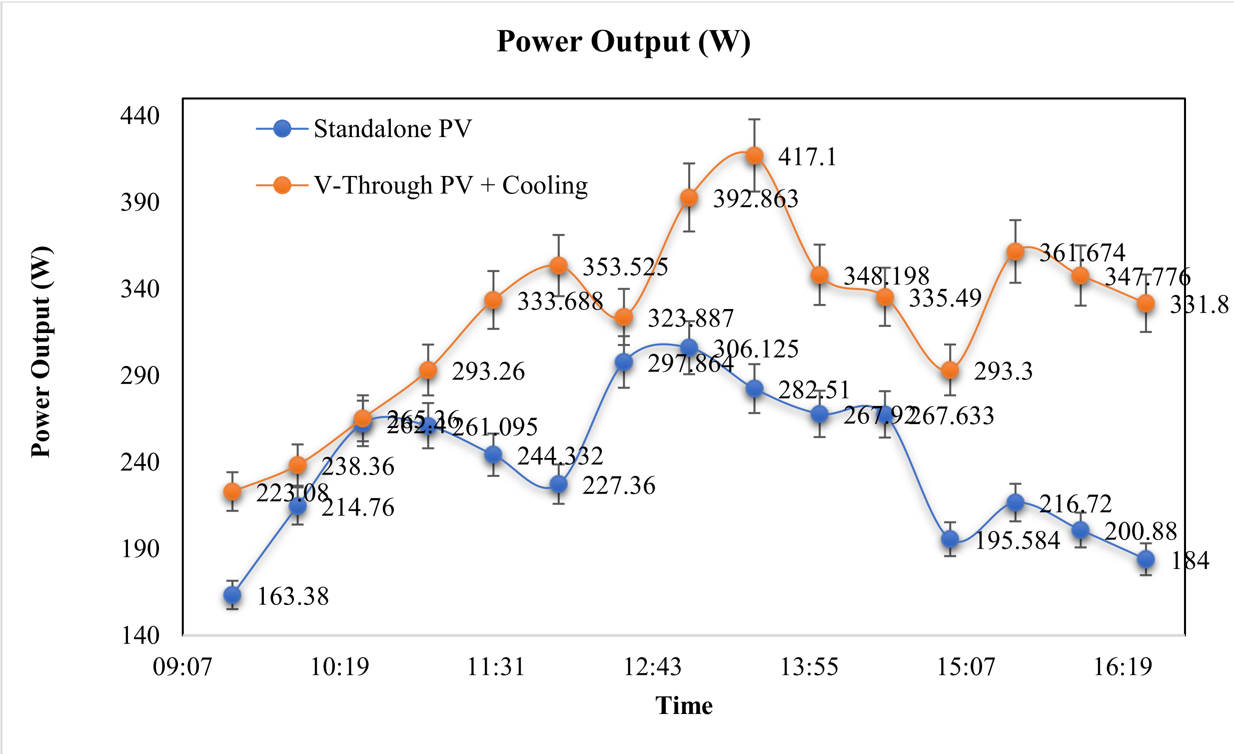


**Fig. 5 Comparative of power output for V-Trough with front Cooling vs. Standalone PV panel**

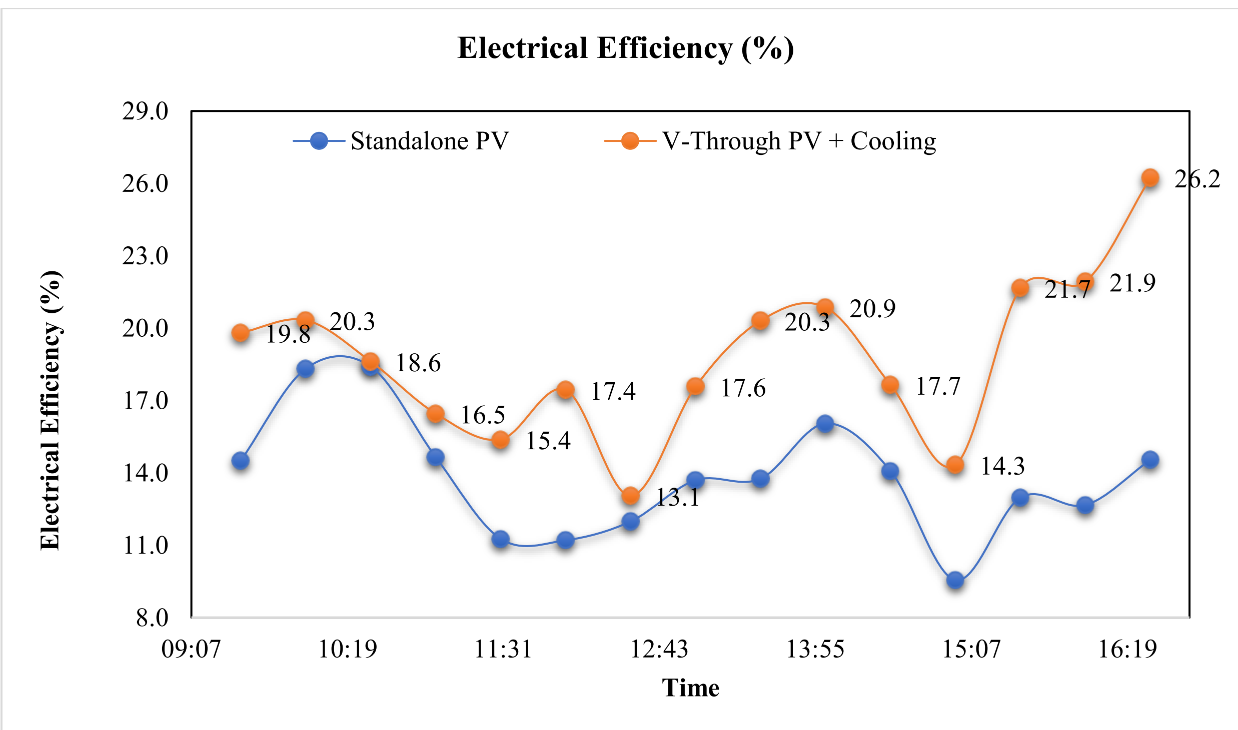


**Fig. 6 Comparative of electrical efficiency for V-Trough with front Cooling vs. Standalone PV panel**

Figures 5 and 6 show the power and efficiency of PV, respectively. Both graphs confirm that power and efficiency increase during the afternoon period. The reason for this behaviour is that the temperature is the critical factor at afternoon, which also leads to the most significant parameter for the cooling effect. These trends proved that controlling temperature can improve the performance of PV during the hottest conditions of the day.

The experimental results clearly showed that the integration of a V-Trough PV with front surface water cooling has improvements in both thermal and electrical performance of the PV. Cooling system helped improve the increase in the surface temperature because of solar concentration, allowing the PV to run at extremely low and constant temperatures and produce the electrical power and conversion efficiency.

The power enhancement was an average increase by 35.26% up to the maximum increase by 61.71%. These numbers showed the system model as valid for many power productions as well as for the particular usage for solar-operated RO desalination system. The results showed the potential of integrating PV with V-Trough and front Cooling to improve the performance.

A comparative study between the present investigation and similar previous studies using a V-trough concentrator in combination with the PV cooling arrangement is summarized in Table 4. In the studies cited, the water flow rate utilized were in the range of 25 LPH to 144 LPH and 0.25 kg/s, whereas for the present investigation, the flow rate employed is 90 LPH.

In the present study, PV temperature was found reduced from 61°C to 33.4°C, which around 27.6°C of surface temperature was cooled down. This comparatively found a similar patten from literature, that result presented by Elminshawy et al. [18], and Michael et al. [22], were found reduction in surface temperatures. As far as the power output improvement is concerned, the present investigation has yielded an improvement in power up to 28.4%, which is similar to that obtained by Elminshawy et al. [18] (28.3%) and higher than that by Ghasemian et al. [19] (14%). Though maximum improvement was achieved by Michael et al. [22], where power had been boosted up to 39%, it had shown decent enhancement in electrical output with a fairly basic cooling mechanism.

The efficiency improvement by the present study is recorded up to 11.7%, which is similar to the value of 12.6% obtained by Ghasemian et al. [19].

**Table 4. Comparison of the present study with previous research**

| Parameter | Reference study of PV with V-through and cooling system | | | Present Study |
|---|---|---|---|---|
| | Elminshawy et al. [18] | Ghasemian et al. [19] | Michael et al. [22] | |
| Cooling flow rate | Up to 144 LPH | 25-150 LPH | 0.25 kg/s | 90 LPH |
| Temperature reduction | 72.5 to 39.3°C | Up to 12°C | 98.2 to 58.3°C | 61 to 33.4°C |
| Power improvement | Up to 28.3% | Up to 14% | Up to 39% | Up to 28.4% |
| Efficiency improvement | - | Up to 12.6% | - | Up to 11.7% |

**Table 5. Statistical summary and uncertainty analysis of power output of solar PV panels**

| Parameter | Unit | Standalone PV | V-Trough PV + Cooling |
|---|---|---|---|
| Mean Power Output, μ | W | 239.5 | 323.9 |
| Standard Deviation, σ | W | 43.0 | 53.4 |
| Minimum Power Output | W | 163.4 | 223.1 |
| Maximum Power Output | W | 306.1 | 417.1 |
| Coefficient of Variation, CV | % | 17.9 | 16.5 |
| Uncertainty | % | ±2.06 | ±2.06 |
| Absolute Power Uncertainty (W) | W | ±4.93 | ±6.67 |

### *3.4. Statistical Analysis*

Statistical analysis was carried out to determine variability, stability, and uncertainty of the system for experimental data and to validate the importance of the measured performance. Table 5 demonstrates the statistical summary and uncertainty analysis results of the standalone PV and the V-Trough PV with surface cooling.

The mean power output of standalone PV and V-Trough PV was found by 239.5 W and 323.9 W, respectively. This representing an improvement in electrical performance and is more likely to implement of combined optical concentration and water-cooling approach. The results describe the high electrical performance for modified PV throughout the experiments and specially in peak operating conditions.

The standard Deviation (σ), which is the distribution of mean power output, was found by 43.0 W and 53.4 W for standalone PV and V-Trough cooled PV, respectively. Even if the absolute values are higher for the modified system, variability for the standalone and V-Trough PV is measured by CV. Normally, standard deviations are represented by means of normal distribution as: The CV value for standalone PV and V-Trough PV with Cooling was evaluated to be 17.9% and 16.5%, respectively. Small values of CV represent better operating stability of the system with good power output. The value shows that water cooling from the front-surface mainly cools the system, which reduces the power fluctuations during maximum solar irradiation. Minimum power output for standalone PV and V-Trough cooled PV was determined to be 163.4 W and 223.1 W, respectively. This showed the higher performance of modified PV compared to standalone PV during early-morning and late-afternoon. Similarly, the maximum power output of standalone PV and V-Trough cooled PV was found by 306.1 W to 417.1 W, respectively. This illustrates the excellent performance at high working conditions.

Uncertainty has been evaluated through the standard error method using the accuracy of voltage and current measurement. Uncertainty of power output has been found to be 2.06% for both the PV systems. An absolute uncertainty calculated for standalone PV and V-Trough cooled PV by ±4.93 W and ±6.67 W, respectively. These uncertainties were smaller than the mean power output difference between the two systems. This confirms the performance improvement was statistically significant and not affected to any measurement error.

## 4. Conclusion

The present study was experimented the performance of a V-Trough PV with front surface water cooling to provide electricity for operating the RO system. A comparative test was performed by using a self-standing PV, which operated under atmospheric conditions, to evaluate the thermal and electrical performance and the validity of the modified system.

The experimental results showed that front surface water cooling is advantageous for reducing the temperature gain due to high solar irradiance and optical concentration. The modified PV works at a lower temperature during the whole day, where the maximum temperature decrease is 29.16°C with an average decrease of 24.6°C comparing with PV standalone. It was good for electricity performance at lower temperature, also there was not as much performance degrading as compared at the higher surface temperature.

Electrical performance revealed that the V-Trough PV with Cooling has a higher mean power output of 323.9 W compared to 239.5 W for the standalone PV, which shows 35.26% improvement in power output and a maximum up to 61.71% during peak operating conditions. Statistical analysis showed the robustness of the system, as the coefficient of variation for the modified PV system (16.5%) was lower than that of standalone PV (17.9%), which has higher operational stability. Furthermore, uncertainty analysis showed ±2.06% for power output, which was lower than the improvement in performance of the modified system. This shows the modified system is statistically significant than a result of experimental error.

The electrical efficiency was also improved in V-Trough PV due to the combined effect of increased solar irradiance and thermal load regulation using front surface cooling. The modified system gives a higher efficiency throughout the experimental period, especially during peak hours, where standalone PV have severe thermal losses.

In conclusion, through the experiments, it was observed that there is an optimal and implementable configuration for a V-trough concentrator cooled at the front surface by water flow that provides good thermal and electrical efficiency for a hot climate. The stable and enhanced power output, which has been experienced to get increased performance, demonstrated the suitability of the system for the RO systems.

### *4.1. Study Limitations and Future Research Directions*

Along with the potential results of cooling surface PV experiments, the current work has some limitations. Experimental analysis was carried out in a short duration on a clear sky day. Fluctuations and variability of the ambient parameters, namely ambient temperature, humidity, and solar irradiation on an annual basis, would surely cause variations in the PV performance in the long run. Thus, studies need to be carried out in different seasons to analyse annual performance.

The study was carried out at a single geographical location, which has limited results, which may vary in other climatic regions. The results of V-Trough PV with front surface water cooling may vary under different atmospheric conditions.

There is a fixed tilt angle and geometry of V-Trough PV, and a constant water flow rate. The system was not optimized with a variation of operating conditions. Other system parameters, such as reflector angles, concentration ratio, and cooling water flow rate, can be optimized to enhance the system performance by using very few system resources. A thorough, energetic, and economic study could also consider evaluating the global efficiency of the whole system (considering water, consumption, pump energy, and life-cycle cost) to study a practical implementation of the concept.

The effects of material degradation, scaling, or fouling to the cooling flow and maintenance of the cooling system for the long term were not considered in this paper. However, they are significant for actual implementation.

The sensitivity of the system to changing operating conditions (water flow, reflector geometry, climate conditions) as well as its long-term durability to extended operation outside should also be part of future studies.

In this work, the proposed system is evaluated in an experimental setup as a standalone, and it doesn't work with the integration of a battery energy storage system, with grid connection, and in a hybrid renewable energy system. It could be the integration of the proposed PV-based V-trough-water cooling system with energy storage and hybrid renewables in the future to make its operation more robust and to handle with fluctuating sunlight. Further research into scaling should be conducted to investigate the technical and economic viability of implementing the proposed configuration for larger PV-powered reverse osmosis desalination systems, as well as community-sized water treatment.

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## Conflict of Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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